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I. Illumination and Visual Capacities

(A Review of recent Literature)

BY

R. J. LYTHGOE, M.A.. B.Ch.

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INTRODUCTION

During recent years the attention of the Medical Research Council has been increasingly drawn to the need in this country for more active and extensive research work in the physiology of vision. Very little work in that subject is being done at any of our Universities, and few, if any, recruits to it are in sight. The need, however, is urgent, both for the advancement of primary knowledge as such, and for meeting the practical requirements, present and prospective, of various Government Departments and, more generally, of the medical profession.

A sufficient indication of some immediate needs of this kind was given in 1924, when the Council were requested by the British Medical Association to consider a resolution unanimously adopted at a meeting representative of ophthalmologists from all parts of the United Kingdom. In the terms of this resolution the Association were recommended 'to press strongly upon the Government the great need for research upon many unsolved problems of vision in relation to the requirements of the combatant services'.

The Medical Research Council, after consultation with the Admiralty, the War Office, and the Air Ministry, appointed a Committee to initiate and supervise research work in the physiology of vision, to co-operate with other Government Departments, especially the Service Departments, in studying problems involving questions of vision, and in so doing to promote so far as possible the attention paid to the subject generally at the Universities and other centres.

At an early stage it appeared to the Committee that a critical survey of the work already done in this and other countries in some parts of the applied physiology of vision would be useful to them in planning their programme of research. The Council accordingly made arrangements for Mr. R. J. Lythgoe to prepare the analysis of the more recent work upon the relation of illumination to visual capacities which is given in the present report. The Council share the view of the Committee that the publication of this survey may assist other workers, especially in a field where the contributory studies here brought together in summary are numerous, and widely scattered in time and place.

Medical Research Council,
15 York Buildings, Adelphi,
London, W.C. 2.

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ILLUMINATION AND VISUAL CAPACITIES

(A REVIEW OF RECENT LITERATURE)

By R. J. Lythgoe, M.A., B.Ch.

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DEFINITIONS

(Taken for the most part from *Walsh* (1923.)

The unit of luminous flux is the **Lumen.** It is equal to the flux emitted in a unit solid angle by a uniform point source of 1 international candle.

Luminous intensity (C.P.) of a point source in any direction is the luminous flux per unit solid angle emitted by that source in that direction.

The unit of luminous intensity is the **International Candle.** The illumination at a point of a surface is the surface density of the luminous flux at that point or the quotient of the flux by the area of the surface when the latter is uniformly illuminated.

The practical unit of illumination is the **Lux.** It is the illumination of a surface 1 sq. m. in area receiving a uniformly distributed flux of 1 lumen or the illumination produced at the surface of a sphere having a radius of 1 m. by a uniform point source of 1 international candle situated at its centre.

Taking the cm. as the unit of length, the unit of illumination is the lumen per sq. cm.; it is known as the **Phot.** Taking the foot as the unit of length, the unit of illumination is the **Foot-Candle** (fc.). 1 foot-candle = 10·764 metre-candles (mc.) or Lux = 1·0764 milliphot. 1 Metre Kerz (Hefner Unit) = 0·9 international metre-candle.

The brightness of a luminous surface in a given direction is the C.P. per unit projected area of the surface in that direction. It is expressed in candles per sq. mm. or sq. m. 1 **Lambert** = 1,000 **Millilamberts** = the brightness of a perfectly diffusing surface radiating or reflecting 1 lumen per sq. cm. A surface emitting 1 lumen per sq. ft. will have a brightness of 1 Foot Lambert or 1 equivalent foot-candle = 1·076 millilamberts (ml's.) = 0·318 candles per sq. ft.

1 **Photon** is the unit of retinal illumination = 1 candle per sq. metre per 1 sq. millimetre of pupil.

1μ = 1 thousandth part of 1 millimetre.
$1m\mu$ = 1 millionth part of 1 millimetre.
1σ = 1 thousandth part of 1 second.

The names given to the colour sensations produced by different regions of the spectrum are as follows (v. Helmholtz):

Fraunhofer line.	*Wave-length in $m\mu$.*	*Colour.*
A	760·40	Extreme red.
B	686·853	Red.
C	656·314	Junction of red and orange.
D	589·625 589·024	Golden yellow.
E	526·990	Green.
F	486·164	Cyan blue.
G	430·825	Junction of indigo blue and violet.
H	396·879	Limit of violet.

THE INFLUENCE OF DIFFERENT INTENSITIES OF ILLUMINATION ON VISUAL ACUITY

The physiological elements involved in visual perception have been quoted by *Parsons* (1914 *a*) as:

1. The visual sense of position (*Optischer Raumsinn*).
2. The visual resolving power or discrimination (*Optisches Auflösungsvermögen*).
3. The form sense (*Optischer Formensinn*).

To these three grades are adduced three criteria: (1) the minimum visible, (2) the minimum separable, (3) the minimum cognoscible (Hess), respectively. The form sense is dependent on the visual resolving power and sense of position, but is essentially a psychological problem. The resolving power and sense of position have been studied by physiologists with respect to the following variable factors:

1. The intensity of illumination.
2. The contrast.
3. 'Irradiation in its broadest meaning.'
4. 'The state of adaptation of the retina and the size of the pupil.'

It is with these variable factors that the first section of abstracts deals. As with most physiological research, one variable can rarely be investigated whilst the others are kept constant, so that it must be borne in mind that the subdivision of the material is to a large extent artificial, and that the subject-matter in the papers of one section may overlap that in another.

1. Illumination and Standard Test Objects.

(For work prior to 1914 see *Parsons* (1912–14).) *Hulshoff* (1917) used the Straub modification of Snellen's prongs and varied the illumination and contrast. She found that at an illumination of 37 metre-candles the visual acuity was 1: it was less for 10 metre-candles, whilst at 140 metre-candles it was 1·1. Using an illumination of more than 40 metre candles there was very little increase of the visual acuity if the contrast was large, but with small contrasts it had a marked improving effect. The same illumination shows up a small contrast more on a bright than on a dark field.

Roelofs and *de Haan* (1922) graded visual acuity into:

1. The minimum distinguishable.
2. The minimal separable for points (*Empfindungskreis*).
3. The minimal separable for lines (*Empfindungsbreite*).
4. The minimal distinguishable change of contour (*Richtungsunterschied*).

The investigation was a continuation of the work by *Roelofs* (1917) and *Guillery* (1896), who devised experiments to show that the recognition of shapes is not served by the same function as the percep-

tion of the minimum separable. They included the work on minimum change of direction in consequence of *Straub's* definition of visual acuity as the ability to detect differences of contour.

Four types of test object were used, one for each grade of visual acuity. They were: a large ground on which was a small square for the minimum distinguishable; small squares separated by a distance equal to their sides which had to be distinguished from a rectangle of equal total size for the minimum separable (points); groups of three rectangles pointing in different directions for the minimum separable (lines); and two rectangles in the space between which was a square slightly out of line for the minimum perceptible change of contour.

The test objects were made of pieces of paper pasted on cardboard and were arranged in twelve rows of different sizes. The sizes of the sides of the squares ranged from $\frac{1}{2}$ to 30 mm. Each type of card was made in six different ways so as to investigate the effects of contrast on visual acuity, viz. white on black, light grey, and dark grey; black on white, light grey, and dark grey.

Two methods of observation were employed:

(*a*) The subject remained in the darkened room for twenty minutes so as to become dark adapted. The diaphragm of the source of light was then opened slowly, and the size of the opening necessary to read each line of characters was recorded. The observer sat at a distance of four metres from the types.

(*b*) The illumination was fixed and the distance at which each size could be read was determined.

The observations by each method were repeated five times. There were 2,880 observations made in all. Precautions were taken against suggestion to the observer: the whole research was very carefully carried out.

At a scale reading of 9,474 units the brightness of the various surfaces used was: white, 15 M.K.; light grey, 4·7 M.K.; dark grey, 1·9 M.K.; black, 0·75 M.K.

These were the highest values: they could be reduced to 1/7,500.

The results were quoted in detail, and for each set of observations a graph was drawn showing the relation between the log. of the illumination and the log. of the size of the angle subtended at the eye.

Each set of data was subjected to an elaborate statistical analysis. Their conclusions can be summarized as follows:

For the minimum distinguishable $I = K \dfrac{1}{\alpha^{2\cdot2-2\cdot4}}$.

For the minimum separable (squares) $I = K' \dfrac{1}{\alpha^{2\cdot16-2\cdot34}}$.

For the minimum separable (lines) $I = K'' \dfrac{1}{E_b^{2\cdot4-2\cdot5}}$.

Where I = illumination, α = angle subtended by side of square, E_b = angle subtended by breadth of line.

For the minimum difference of direction the results were not consistent.

Within limits a closer approximation can be made:

$I = K \frac{1}{\text{Area}}$, where the area is that of the square in question. They believe that this is the true statement and that the deviations from this value at extremes of illumination are due to:

1. Alterations in the size of the pupil. 2. Changes in dark adaptation. 3. The autonomous areas of Charpentier are exceeded at low illumination and at high illuminations the retinal image approximates to that of a single cone.

So far as contrast goes they believe that all their experiments can be summarized in the equations:

$S = K\sqrt{\pm(O-G)}$, where S = Visual Acuity.
O = Illumination of Object.
G = Illumination of Ground.
K = A constant.

$S = K'\sqrt{I}$ I = Illumination.

Comparing the results with the different types of test object they find: when the illumination is constant, then (1) the area of one of the minimum separable points is equal to the area of the minimum distinguishable area; (2) that the diameter of the just perceptible square is four times the smallest difference of direction, and (3) that the diameter of the minimum separable for squares is twice the minimum separable for lines.

The values for the visual acuity and illumination as given by Piekama and Laan are quoted. The relation $S = K\sqrt{I}$ was shown to hold for illuminations of less than 0·25 metre-candles. The deviation at higher illuminations they explain as due to contraction of the pupil. *Petrén* and *Johansson* did similar work on visual acuity and contrast, and their results agree with *Roelofs* and *de Haan*. *Carsten* (1925) used grey letters on a white ground to determine visual acuity at low illuminations.

Ferree and *Rand* (1920 *a–h*) determined the least visual angle at which the direction of the gap in Landolt's broken ring could be appreciated under illuminations of 0·001, 0·005, 0·01, and so on to twenty foot-candles. The broken circle was used in eight positions (differing by 45°). Five out of eight correct judgements were required. The coefficient of reflection of the test object was 85 per cent. The source of illumination was a Mazda B. (tungsten-filament vacuum) lamp. The rise in visual acuity was rapid up to an illumination of about five foot-candles, after which it became progressively slower and reached a maximum at about twenty foot-candles, although the improvement in the later stages was scarcely noticeable. They are of the opinion that the routine testing of visual acuity is best accomplished by alterations in the illumination of the test object, since the illumination can be varied very markedly without making much difference to the acuity, and also since errors of refraction, especially astigmatism, are more marked at low illuminations. They tested the influence of alterations in brightness on the visual acuity for eyes with a slight artificial astigmatic error.

They concluded that astigmatism is most noticeable at low illuminations. They found also that a sixfold increase of illumination may

be necessary to discern the object if it is turned into the most unfavourable astigmatic meridian. With the normal eye an increase of illumination

from 0·001 to 0·1 fc. gave a 4·89-fold increase in visual acuity.
,, 0·1 to 1·0 fc. gave a 67·7 per cent. increase in visual acuity.
,, 1 to 5 fc. gave a 43·6 per cent. increase in visual acuity.
,, 5 to 20 fc. gave an 8·2 per cent. increase in visual acuity.

Basler (1923) carried out a determination of the minimum perceptible shift of a white pointer on a black background with illuminations of 1 to 1,080 metre-candles.

2. Illumination and Certain Visual Performances.

A small amount of work has been done on the effect of alterations of illumination on such functions of the eye as reading, the speed of recognition of standard test objects, and industrial output.

Ferree and *Rand* (1919) used E's as test objects: they could be turned to any angle, and the observer had to say in which direction they pointed. Two distances of the test objects from the eye were employed, 18 cm. and 6 metres, where they subtended 7 and 14·8 minutes respectively. The illumination was kept constant at 5·2 foot-candles. There were two series, in one of which the observer looked first at the near and then at the far test object. The time taken varied from 0·50 to 1·16 seconds. In the second series the observer looked first at the near, then at the far, and back at the near test object. Here the time varied from 0·96 to 1·76 seconds. The same authors (1920, 1922) measured the 'speed of discrimination' by the reciprocal of the threshold time. As test objects they used the Landolt broken circle which subtended angles from 1·15 to 3·45 minutes and illuminated by white (0·4 to 12 fc.) and spectral lights of varying intensity. See also *Ferree* and *Rand* (1920 *h* and 1924). *Wager* (1922) made a similar investigation.

Lux (1920) measured the amount by which a fixed difference of brightness can be increased or decreased in order that the performance of a piece of work, to which the eye has got accustomed, may not be interfered with, and all the details seen as clearly as before. The time taken for this readjustment to greater or smaller differences of brightness is proportional to the increase of illumination, and varies with the fineness of the work. *Kallenbach* (1921) discusses the results. *Ruffer* (1925) has made a variety of psychological tests at different intensities of illumination.

Considering the importance of the problem surprisingly little work has been done on the influence of illumination on the speed of reading. *Richtmyer* and *Howes* (1916) describe a method where the reader was required to read aloud a definite number of words as rapidly as possible, at several different illuminations. Each specimen to be read contained the same number of typewritten words promiscuously arranged, each word containing two syllables and six letters. The curves show that with all observers the speed of reading increased very rapidly up to an illumination of 0·5 foot-candles, after which value there is little change. As was to be expected there were considerable individual variations. Rough determinations were also

made on the effects of a glaring source of light on the speed of reading. A 60-watt lamp was placed in front of the reader, 15 degrees to the left of his line of vision, and in such a way that the light shone into his eye but not on to the type. The decrease in the speed of reading compared with the previous results is not obvious; there was no appreciable difference between a plain and a frosted lamp (cf. *Bordoni* (1924)). A curve is given showing the relation between the speed of reading and the angle made by the glaring source of light with the line of vision. There is a steadily increasing disability as the angle is made smaller. The speed of reading was also very much decreased when the indirect source of light used in the first experiments was replaced by one which gave specular reflection from the print into the eye of the observer.

Luckiesh, *Taylor*, and *Sinden* (1921) used Old English characters instead of the ordinary forms of type; they claim that with the latter recognition of groups of letters makes the results less valuable. Photographic copies of a sheet of the Old English type were made, one set of which was fogged so as to reduce the contrast between the letters and the background, the reflection coefficient of which became 22·5 per cent. Observations were made at 3·12, 6·25, 12·5, and 25·0 fc. with the low contrast, and 0·39, 1·56, 6·25, and 25·0 fc. with the high contrast. The sheets of type were mounted on a drum in a closed box illuminated from inside. The drum could be rotated at a constant speed. The observer started to read, and the speed of the drum was gradually increased until the observer could just keep pace with it, over a period of several minutes. Forty-nine observers took part. The results show that the effect of increasing the illumination is very much more marked with the low than with the high contrasts, and also that whereas the speed of reading tends to assume a steady value above 10 fc. for the high contrasts, for the low contrast it continues to increase to the highest illumination used (25·0 fc.).

The illumination chosen by the observers as the most comfortable for reading was also determined both for the ordinary gas-filled lamp and the mercury arc. That chosen for the mercury arc was 4·20 per cent. higher, whereas 75–95 per cent. less would have given equal visual acuity. As is to be expected the results of different observers vary considerably.

Kirsch (1920), *Radojevic* (1922), and *Wick* (1921) were concerned with the two types of printed characters employed in Germany; *Bentley* (1921) with the influence of different distances between lines of print on legibility. See also *Gould*, *Raines*, and *Ruckmick* (1921) on the ease of reading the backbone titles on thin books and magazines.

Israel (1923) determined the monocular and binocular perception of depth at low illuminations of 0·0005, 0·0018, and 0·0117 foot-candles. The results are difficult to interpret.

A great deal has been done on the influence of illumination on industrial output. Such work as that of Thompson, Schartz, Ives, and Bryan may be quoted. A full bibliography will be found in the Illumination Index of the Transactions of the Ill. Eng. Soc. (N.Y.), and a comprehensive treatment of the subject is given by *Luckiesh* (1924).

Arps (1917) studied the effect of different intensities of light on the

visual discrimination for the sizes of small rectangles. He employed six white oblongs, 15 × 40 mm., and six oblongs varying in length from 38·5 to 41·5 mm. A standard oblong (15 × 40 mm.) was shown to the observer, and two seconds afterwards one of the variables. There were nine grades of lighting from 0·2 to 8·2 C.P. The experiments were conducted with the rectangles horizontal, vertical, and at an angle of 45° to the line of sight.

It was found that judgement was better in the horizontal and vertical positions than in the oblique position. In very few cases were errors of more than 0·75 mm. made. The range of illumination used had no consistent effect on the discriminative ability. There was a marked practice effect.

French (1917) considered that the accuracy of contact setting of a vernier is unaffected by large differences of illumination. The reduction of the illumination by 1,000 had no appreciable effect.

THE EFFECT OF VARYING THE CHARACTER OF ILLUMINATION ON VISUAL ACUITY

1. Monochromatic Illumination.

Many of the early workers on visual acuity determined the ability to read printed characters in various parts of the spectrum and in other sources of monochromatic illumination. Macé de Lépinay et Nicati (1881–3), working alone, and also with *Uhthoff*, found that it is possible to obtain the same maximal visual acuity with sources of light of any colour provided sufficiently high intensities are used. Taking as the unit of intensity for the coloured light in question that intensity which gives a visual acuity of 0·33, they measured the intensity necessary to give other visual acuities. The results are given in Table I.

Table I.

Visual Acuity.	*Intensity of Illumination at different wave-lengths.*				
	507 $m\mu$.	497 $m\mu$.	458 $m\mu$.	442 $m\mu$.	428 $m\mu$.
0·47	5·0	8·18	—	—	—
0·42	2·67	3·71	5·48	6·51	—
0·33	1·00	1·00	1·00	1·00	1·00
0·26	0·48	0·36	0·22	0·21	0·18
0·22	0·33	0·23	0·13	0·12	0·10

From the table it will be seen that the illumination can be varied very considerably in the blue end of the spectrum without affecting the visual acuity materially. A similar alteration of illumination in the red end produces greater changes. The conclusion was that visual acuity is dependent chiefly on the less refrangible rays.

Uhthoff (1886–90) confirmed and extended the results. Details and references to this and other work will be found in Parsons (1914 *b*). Other workers are Celsius (1735), Buffon (1743), Herschel, Snellen and Landolt (1887), *Langley* (1888), *König* (1876), *Broca* and *Laporte* (1908), *Asche* (1909), *Wertheim* (1890), *Guillery* (1896), Loeser (1909), Nagel (1909), *Schneider* (1924). Very few of these measured the

illumination. *Cohn* worked with monochromatic sources having an illumination of thirty-six metre-candles. He found the following values for the visual acuity: white, 2·0; yellow, 2·15; red, 2·0; green, 0·66; blue, 0·37.

Charpentier (1882) used his familiar test of the illumination necessary to discriminate dots as separate with different illumination colours secured by using blue, red, green, and yellow glass.

Brücke (1879–81) measured the maximum distance for the recognition of the direction of squares of one colour arranged in chess-board pattern on a ground of another colour of equal brightness. He expressed his results as a ratio (distance at which white on black) ÷ (distance at which the coloured squares could be discriminated). The lowest was for green and cinnabar (1·4) and the highest for ochre and blue (1·7). *Örum* (1904) measured the distance at which a dot pattern illuminated by different coloured lights could be read when the illumination was increased. Dyes were used to produce the colours. The visual acuity appears to be lower for all colours than for white, but the results are given in such a way as to make comparison impossible.

Dow (1909) used the method of *Laporte* and *Broca.* Lantern slides, on which fine detail had been photographed, were viewed so that each half was illuminated from behind by a different coloured light obtained by gelatine filters. He draws a distinction between the apparent brightness of the test objects and the sharpness of the detail. It was, in fact, possible to secure greater sharpness of the pattern with light of a certain colour, in spite of an obviously lower order of illumination. Graphs are given for the relation between illumination and acuity for red and green lights. The acuteness of vision improves rapidly after an illumination of 0·5 metre-candles for both colours. His main conclusion is that 'the blue-green end of the spectrum is somewhat advantageous for very close work, but not so good as red light for the illumination of objects or patterns to be distinguished at a distance'.

Ashe (1909) compared the visual acuity of red, green, blue, and white sources of light. The measure of the visual acuity was the distance at which print could be read, and it ranged from about 50 to about 4,000 cm.: the illuminations were all below 5 M.C. for the coloured lights, and went up to about 40 M.C. for the white light. Ranged in order of merit the light sources were white, blue-green, and red for equal intensities of illumination. The results are explained on a supposed greater ability of the coloured lights to contract the pupil.

Bell (1911 *a* and *b*) compared the visual acuity in a tungsten light with that in a mercury arc lamp. He found that for equal brightness the mercury lamp yields a higher visual acuity, which he believes is due to the more homogeneous nature of the light and the consequently better resolution by the eye. *Luckiesh* (1911 *a*, *b*, *c*, 1912) confirmed Bell's observations, and extended them by using lights of the same colour but of different spectral composition. This he achieved by the use of absorbing solutions. As a criterion of visual acuity he used the ability to read a page of type, and the illumination was increased in each case till this could just be done. The results are given in Table II.

Table II.

	Source.	Colour.	Approximate Foot-candles.	Relative Illumination for equal Visual Acuity.
1.	Mercury Arc	Green Line	2.0	1.00
	Tungsten	Green		1.75
2.	Tungsten	Yellow	4.0	1.00
	Tungsten	Yellow (different shade)		1.33
3.	Sodium Line	Yellow	0.5	1.00
	Tungsten	Yellow		1.66
4.	Mercury Arc	Green	0.5	1.00
	Tungsten	Green		5.10

In general, where the discrimination of fine detail is in question, a monochromatic illumination is better than a mixed light source such as daylight. Further experiments by this author show that monochromatic lights differ in their 'defining power', and that yellow is superior to others in this respect. For any given change in the brightness of the test object, the change in visual acuity was least for monochromatic light. *Rice* (1912) also worked in this field. (See also p. 43.)

Elliot (1922) measured the time required to read and to name correctly a group of numbers illuminated in turn by sunlight, a tungsten glow lamp, and a mercury vapour arc. Illuminations ranging from ½ to 50 foot-candles were used. The time required is not clear from his paper. In general there is a rapid decrease in the cognitive time up to an illumination of 10 foot-candles; beyond this value increase of illumination has very little effect, except in the case of the mercury lamp, where there is a slight improvement. He finds that the time required to read correctly is less in all cases for a mercury lamp than for sunlight, and that the speed of reading is less than either for a tungsten lamp at similar illuminations.

Weber (1884) and *Luckiesh* and *Moss* (1925) determined the effect on visual acuity of shortening the blue end of the spectrum. The latter claim that a yellow potassium bichromate filter which reduces the brightness of a test object by 46 per cent. leads to no decrease in visual acuity and may cause a rise. They used a Madza C gas-filled lamp.

Ferree and *Rand* (1918) estimated the relative merits of different common illuminants on visual acuity, using their test lantern and the Landolt broken circle. They found considerable differences between the various types of tungsten lamps, carbon lamps, and the kerosene flame. The ordinary 'nitrogen' lamp appears to be most conducive to efficient seeing, whilst the semi-daylight lamp is least conducive, the kerosene lamp lying somewhere between the two. These authors have also done a considerable amount of work on various types of illumination fittings (luminaires); see *Ferree* (1913–15), *Ferree* and *Rand* (1916 *d* and *e*, 1917).

As regards the influence of coloured lights on visual acuity, they summarize their results in saying that spectral lights give greater clearness of seeing than mixed coloured lights of the same hue, saturation, and luminosity; but white light made up of all the wave-lengths of the spectrum gives a better power to discriminate

the details on the printed page than any coloured light of equal luminosity even though of spectral purity. The hues in the mid-region of the spectrum are the most favourable for the colouring of a page of print. Ranked in order of merit from best to worst, they are: yellow, orange-yellow, greenish-yellow, orange, green, red, blue-green, and blue; but all colouring is inferior to white if the printed characters are to be black (1925).

Kohlrausch (1923) determined the visual acuity for fine black lines on a coloured background. The determination was one of a series in which all methods of heterochromatic photometry including the stereo-comparator were employed.

Babbage (1827) investigated the best colour for the printed page.

A considerable amount of work has been done, from the industrial output standpoint, on the maximal illumination and the method of lighting the factory, workshop, &c. All references will be found in the Illuminating Index, Transactions of the Illuminating Engineering Society (N.Y.).

For the theoretical aspect of the resolving power of the eye for different colours see *Hartridge* (1918, 1922).

2. Intermittent Illumination.

Parker and *Patten* (1912) measured, radiometrically, the light energy of two components of a source of light which were equalized for brightness. The brightness of one component was cut down by a diaphragm and of the other by a sector rotating 1,750 revolutions per minute. They do not state if flicker was observed; the open sector in the disk had an angular aperture of 16·7°. It was found that when equally bright perceptually the physical intensity of the beam transmitted through the sector was 5·9 per cent. greater than that of the beam transmitted through the diaphragm. They claim that their results are well outside the average probable error. Rotations of 540, 775, 940, 1,200, and 2,950 revolutions per minute gave similar results. These results seem to be contradictory to Talbot's law, but most of the accurate work on the latter has been done at speeds where there is complete fusion of impulses (*Lummer* and *Brodhun* (1890–6), *Hyde* (1906), *Saltmarsh* (1915)).

Ebbecke (1920) investigated the apparent brightness and colour of objects illuminated by single flashes and also by flickering light sources.

THE DISCRIMINATION OF SHAPES AND DIFFERENCES OF BRIGHTNESS

1. The Discrimination of Shapes.

[For the work on this subject up to 1914 see *Parsons*.]

Baker and *Bryan* (1912) found that two lines can be set in coincidence, two shapes can be set in contact, or the space between two parallel lines can be bisected with a mean error of the order of 10 secs.

French (1919), in a continuation of his work on the difference threshold and size of visual field, measured the accuracy with which

two circular images could be adjusted for coincidence. The images, which were produced by a double-image prism, were made to overlap to varying degrees by altering its position. When the overlap is only partial there will be a central area more strongly illuminated than the two flanking crescents. In general the central part appears brighter only if the total angle is not less than four minutes.

In another series he used two holes which were duplicated by a double-image prism and illuminated from behind. The two centre images were made to approach one another by a longitudinal movement of the prism. Readings were taken when the two circles appeared just to touch, when the two circles appeared to be one ellipse, i.e. when the indentation had apparently disappeared, and again when the coincident images assumed one circular form. The experiments were repeated for several sizes of circle. He gives no record of the illuminations employed.

The results show that there is always a tendency to over-estimate the sizes of the circles, i.e. they appear to be in contact, whereas they are really separated. The error becomes increasingly more serious as disks progressively smaller than three minutes are used. This result is explained as being due to diffraction occurring at the edge of the pupil, when the eye was accommodated for the small amount of light.

He next did some experiments on the accuracy of setting a vernier scale. Black lines 0·43 of an inch wide on a white ground were used. He found that the precision error was 0·63 seconds of visual angle. By precision error he means the average accuracy with which an observation can be repeated irrespective of its absolute accuracy. He varied the thickness of the lines, and found that the finer the lines the greater is the precision of setting. He also found that the accuracy of setting is smaller when the height of the lines is less than six minutes and is very poor at 0·6 minutes.

Schulz (1920 *a*). The accuracy of coincidence settings of range-finders is usually taken as ten seconds. Schulz used two black rectangles 50 mm. wide and of varying lengths, and measured the ability to set them in coincidence with a × 6 monocular at 160 metres. The use of the monocular is said to eliminate errors due to accommodation. He found that as the length of the line is increased there is an increasing accuracy of setting, but that for ordinary objects the minimum error may be taken as ten seconds. With objects inclined towards one another at an angle of 45° the error is increased to thirteen seconds. *Dale* (1920), by the double-image prism method, measured the accuracy of setting two circles in contact, using white circles on a black background and vice versa. The illumination was such as just not to produce the 'star appearance'. She used diaphragms of various sizes as artificial pupils in some of the tests. For the natural pupil the apparent was larger than the true angular diameter except for very small disks, where an almost constant apparent diameter of two minutes was obtained. With an artificial pupil of 3·8 mm. diameter the apparent angular diameter was always greater and showed a similar tendency to reach a constant value for small disks.

Schulz (1920 *b* and 1921) worked on the reading of scales on instruments, the difference of apparent size of equally long vertical

and horizontal lines, and the accuracy attainable by colorimetry and polarimetry. For scales to be read to one-tenth of a division, the large marks must be fine and not closer than 0·6 mm. See also *Schulz* (1919) and *Kühl* (1920).

v. Hofe (1920) made some observations on the accuracy of setting coincident lines in range-finders. The error in visual angle is 5·8 secs. to 1·7 secs., depending on the inclination of the lines.

Roelofs (1922) worked on the appreciation of differences of direction. His work is abstracted elsewhere (see p. 7). *Wolfe* (1923) worked on the estimation of the middles of lines. *Hartridge* (1922) did some experiments with a white circle 5 cm. in diameter, having at one point on its circumference, 10 mm. in length, a small excrescence, 2 mm. in width. This was mounted on a sheet of black paper so that the disk could be rotated into different meridians about a pin passed through its centre. The distance was increased until the observer could just indicate the correct position of the excrescence eight times out of ten: the visual angle subtended by it was then eleven seconds. Hartridge can set the absorption bands of his spectroscope in coincidence with the same accuracy.

2. The Discrimination of Differences of Brightness.

The early workers on this subject were Bouguer (1760), Arago (1858), Masson (1845), Steinhil (1837), *Weber* (1834), Fechner (1858), *v. Helmholtz* (1866), *Aubert* (1865), *König* and *Brodhun* (1880, 1903 *a*), *Schirmer* (1890). Weber's Law states that, in the case in point, the just appreciable increase of brightness bears a constant ratio to the original brightness. Fechner's Law is a mathematical derivative from this, and it states that the sensation varies as the logarithm of the stimulus. Two illuminated areas in contact can be seen to differ in brightness if the illumination of one is 1/100 to 1/167 times as great as the other. It is important to bear in mind that the law is true only within limits, and that it breaks down seriously at high and low illuminations, and also if the conditions of the experiment, such as size of field, are not kept constant.

Hecht (1924) collected the work of previous observers on the difference threshold, notably that of König and Brodhun (1888–9) and Blanchard (1918). From these he makes deductions as to the retinal processes involved. Notable amongst these are: (1) That the difference threshold for the cones is considerably less than for the rods, as is shown by a definite break in the curves. (2) That the underlying retinal process is chemical for both rods and cones; when light falls on the retina a bimolecular break-down occurs, with a velocity varying directly as the intensity of light. (3) That for the difference threshold a constant amount of this chemical substance must be broken down in excess of that broken down at the level of adaptation under consideration. (4) That the rate of regeneration of the broken-down substances is quicker for the cones than for the rods, which accounts for the much quicker dark adaptation of the former (three minutes for the cones as opposed to thirty minutes for the rods—*Hecht* (1920)). (5) That the change over from rod to cone mechanism occurs at a brightness of 0·0134 millilamberts.

(6) That there are 572 steps in intensity discrimination. One-third of these are concerned with the rods and two-thirds with the cones. (7) That the chemical break-down theory accounts adequately for the falling off of intensity discrimination at both high and low illuminations.

Lasareff (1911) determined the difference threshold for white light with variable sizes of visual field. He employed the double-image prism method introduced by König in his researches on Weber's Law. By this method the upper half of the visual field can be darkened by rotating a Nicol prism whilst the lower half is kept at constant brightness.

The results are plotted to show the relation between the 'Fechner fraction' $\frac{\Delta I}{I}$ (just noticeable difference of illumination ÷ absolute intensity) and the area of the visual field. Within limits the curve is a rectangular hyperbola given by the equation $\left(\frac{\Delta I}{I}\right) \times (A) = K$, where A is the area of the visual field and K is a constant. If I is kept constant, then it follows that $\Delta I \times A$ is constant or the total increase of illumination is a constant. The size of field varied from 1° 18′ to 6·5′; above 26′ the relation breaks down, and a greater increase of brightness is required than would be expected from the equation. Recalculation of his results is not convincing; the equation $\frac{\Delta I}{I} = \frac{K}{D}$ fits better, where D is the diameter of the field.

There follows a discussion on the influence on the results of the entopic light of the retina, which, it is claimed, explains the hyperbolic portion of the curve.

Reeves (1918 *b*) did a similar piece of work to determine the differential threshold for angular sizes of test-field ranging between 0·33 and 4·92 degrees. For angles larger than 1° he found that the log. of the absolute brightness required to render a given contrast visible is reciprocally proportional to the visual angle, but that the variation is much less for smaller angles.

French (1919) investigated the same problem. He employed two fields separated by an extremely fine line. The illumination of each half was varied in small definite steps of 0·5 per cent. by means of diaphragms. A rough estimation of the effect of illumination on the difference threshold by substituting 16 and 40 C.P. lamps for the 200 C.P. one generally employed, showed that the latter gave a greater accuracy in appreciation of percentage differences of brightness. The ocular of the instrument presumably acted as an artificial pupil. His results can be expressed in the equation $B = \frac{1}{d^{0.52}}$ or roughly $B = \frac{1}{\sqrt{d}}$, where B is the per cent. difference of brightness just distinguishable and d is the angular diameter of the retinal image illuminated. The graph indicates that the *fovea centralis*, especially the very centre of it, is relatively insensitive to differences of contrast. He did similar work with coloured light (q. v.). His results also show that $E = a(B + b)^{0.4}$, where E = per cent. correct estimations in a series of observations; B = per cent. difference of brightness; a and b are

constants. By substituting from actual results it is shown that 'the theoretically absolute uncertainty in the appreciation of difference in brightness is reached when the visual angle is 4·2 minutes'.

Petrén and *Johansson* (1904) also worked on Weber's Law and the central retina.

ADAPTATION AS A FACTOR IN VISUAL DISCRIMINATION

It is a familiar observation that on going into a darkened room after being in bright sunlight one can at first see nothing, but that one's ability to discriminate detail becomes better and better during the next three-quarters of an hour or so; see *Piper* (1903). This is known as 'dark adaptation'. There is no hard-and-fast line of distinction between this phenomenon and the slow recovery of normal night vision after exposure to the glare of a blinding headlight. Similarly, on going into the bright sunlight after a prolonged stay in the dark room, it is found that the ability to discriminate detail is lost. This is called by some writers 'light adaptation'. Again, there is no clear-cut distinction from some of the phenomena of glare. The abstracts in this section summarize modern work on the subject.

1. Retinal Adaptation.

Early workers were concerned with adaptation as measured by the ability to see minimally illuminated light areas, and so measured the dark adaptation of the rods rather than the cones. They were *Aubert* (1865), *Charpentier* (1884), *Nagel* (1911) (see v. Helmholtz, vol. 2, 3rd ed.), *Piper* (1903), *Treitel* (1887), and *Tschermak* (1902).

Inouye and *Oinuma* (1911). A double tube was used through which the two eyes could look simultaneously at differently lighted fields, the illumination being controlled by rotating sectors. One eye was kept light adapted and the other dark adapted by a bandage. The subject perambulated for a given time in a light room, and then rushed into the dark room, tore off the bandage, and compared the brightness of the two fields. By a system of trial and error a setting was reached where the two fields are equally bright. *Dittler* and *Koike* (1912) repeated the above experiments, but used smoked glass instead of sectors. Both sets of investigators obtained a leisurely kind of dark adaptation indicating that they were measuring the rate of dark adaptation of the rods in the peripheral field of view. *Best* (1917) followed the course of the adaptation process for both central and peripheral vision. He used 'Radiolite' screens of various brightness as test objects. He found that the sensitivity in the periphery is doubled in a few seconds at the beginning of dark adaptation, and that at the end of three-quarters of an hour it has increased twelve-fold. Central adaptation is very rapid, but for red is more prolonged than for violet.

In addition to those workers mentioned later, the following worked on foveal dark adaptation: *Nagel* and *Schäfer* (1904), *Wölfflin* (1910), *Tschermak* (1898), *Koster* (1895), *Sheman* (1898), *Petrén* (1904), and others. *Vogelsang* (1924) employed coloured lights.

Nutting (1916 *b*) quotes a table (Table III) for the sensitivity of the eye for contrast and absolute light values at levels of adaptation corresponding to certain common intensities of illumination.

TABLE III.

	Mean brightness level (ml's).	*Just perceptible diff. in illumination.*	*Threshold in ml's.*	*Relative Sensitivity.*	
				Contrast.	*Threshold.*
Exterior daylight	1000	0·0175	0·35	1	1
Interior daylight	10·0	0·030	0·17	59	21
Interior (Night)	0·1	0·123	0·0014	1430	251
Exterior (Night)	0·0001	0·79	0·0001	22300	3090

The sensitivity is got by integrating an expression embracing the reciprocal of the threshold (1909). Working from this basis he followed the course of the dark adaptation of the eye as measured by the increase in light and contrast sensitivity. The apparatus consisted of a piece of white card in which a hole was cut and backed by a piece of opal glass. The latter was illuminated by a Nernst lamp, the intensity of which could be cut down by a wedge. The distance of the observer from the screen was 15 in. The initial adaptation was for 15 min. to a brightness of 0·1 ml's (the brightness of an interior at night). The results are given in Table IV.

TABLE IV.

Time after switching off the light.	*Threshold in ml's.*	*Threshold with a 1·8 mm. diam. artificial pupil in ml's.*
0 min.	0·00131	0·0044
1 ,,	0·00019	0·0020
2 ,,	0·000111	0·00122
5 ,,	0·000054	0·00044
10 ,,	0·000027	0·00021
20 ,,	0·0000088	0·00016
50 ,,	0·0000031	0·00011
60 ,,	0·0000028	
1 hour	0·0000014	
10 hours	0·0000012	

Almost the same results were obtained for a previous adaptation to 2·8 and 0·032 ml's. These results are not quoted.

He also made an investigation to determine 'the effect on the sensibility of the fovea of exposing the retina to illuminations of various sizes, locations, and intensities'. The initial adaptation was, as before, to a brightness of 0·1 ml's: and the area was cut down from 7 cm. to one of 1·5 mm. at 35 cm. The results are given in Table V.

TABLE V.

Solid Angle of Bright Spot.	*Instantaneous Threshold (just perceptible brightness immediately on switching off the light).*
Full field.	0·0019 ml's.
0·43	0·0020
0·16	0·0028
0·016	0·0042
0·0058	0·0092
0·0026	0·0143
0·00065	0·0235
0·00016	0·0300
0 000041	0·0340

Interesting results were got when these small sensitizing fields were made 10 and 1,000 times brighter, as is shown in Table VI.

TABLE VI.

Solid Angle of Bright Spot.	*Threshold at a brightness of sensitizing field in ml's. of 0.1.*	*1.0.*	*100.0.*
Full	0·0019	0·0039	0·19
0·43	0·0020	0·0042	—
0·016	0·0042	0·240	0·025
0·0026	0·143	0·355	0·020

Hecht (1921), in a paper, the sequel to one on peripheral dark adaptation, paid particular attention to (1) the uniformity of the level of dark adaptation. This was done by getting the subject to look at a screen of 90 millilamberts brightness (0·028 candles per sq. cm.), for a uniform time. (2) The subject immediately on ceasing to fixate this screen gazes at the test object. In earlier experiments the light adaptation and measurements were conducted in separate rooms. (3) All readings were corrected for pupillary aperture (*Cobb*, 1915–19).

As a test object, he used a red cross illuminated from behind. The red light was got from a Wratten filter, and passed only rays longer than 650$m\mu$. It had no effect on the rods in consequence. The cross formed an image on the retina which was two-thirds the size of the rod-free area. The illumination of the cross was varied by altering the position of the light behind it. The subject was rested for thirty minutes, and was then adapted to the brightness of the screen for five minutes. The light was then switched off, and he raised his head to the testing apparatus. With a fixed position of the lamp, the time was taken at which the cross just became visible. Fifteen young subjects were used.

Adaptation was very rapid during the first half-minute. A brightness of the cross of about 38×10^{-4} millilamberts was necessary immediately after switching off the light, whilst about 10×10^{-4} mls. were necessary after thirty seconds, about 6×10^{-4} mls. after two minutes, and at the end of the period (twenty minutes) about 4×10^{-4} mls. The experiments were repeated with a white light, and although the absolute values are different, the shapes of the curves remain the same. From this Hecht concludes that Purkinje's phenomenon does not occur at the fovea. Other observers have noted a very slow foveal adaptation to red. The experiments were similar to those of Nagel and Schäfer (1904), who used red, green, and blue lights: they came to the same general conclusions.

Beyne and *Worms* (1924) were concerned with the visual requirements of aviators. The subjects were all about twenty years and with normal vision. They chose 'un éclairement physiologiquement comparable à celui d'une nuit claire, mais sans lune, en un lieu complètement dépourvu de lumières parasites, en septembre à 21 heures'. They measured the visual acuity with a Landolt broken circle under these conditions, and then measured the artificial illumination which would give the same visual acuity in the laboratory. It was found to be about 0·0015 lux. They then measured the visual acuity at this illumination every five minutes after exposure to an illumination of

15 lux. The test lasted thirty-five minutes. Unfortunately the results are very incompletely reproduced. Adaptation appears to be complete in twenty minutes when the visual acuity was between 0·06 and 0·09.

Ferree, Rand, and *Buckley* (1920 *g*) used the apparatus previously described by them. They determined the course of dark adaptation as measured by visual acuity (Snellen's prong). Their conclusions were: (1) That forty-five minutes' dark adaptation considerably decreases the difference in acuity between different individuals as measured by the minimum illumination necessary to recognize the test object. (2) That in 88 per cent. of cases the monocular threshold was higher than the binocular threshold. (3) That the minimum illumination decreases asymptotically in dark adaptation and shows little change after fifteen minutes. (4) That the eye does not gain in acuity by adaptation nearly so fast as it gains in light sensibility.

Dresbach, Sutton, and *Burbage* (1920) followed the course of dark adaptation in the human eye by the flash method. They employed a zone 10–15° from the line of vision and confirmed the observation that the sensitivity increases rapidly for the first half-minute; that it has become two or three times greater in two or three minutes; and that it continues in all for half an hour. *Blanchard* (1918) did similar experiments, but using different brightnesses for the original adaptations.

Reeves (1918 *c*) measured the time which is required after going into a darkened room to detect a fixed contrast with various field sizes and brightnesses. See also (1918 *b*).

Cobb (1919 *a* and *b*) followed the course of dark adaptation for slightly eccentric fixation. The first experiments were made with the test types of De Weckes and Masselon, but it was found that the letters varied in legibility and also that the configuration of the rows of letters made a difference. In consequence he used a test object similar to Nagel's, which consisted of a pair of brass bars cut in a movable disk. The pattern was projected onto a translucent screen, whilst just above the image was a small red spot used as a fixation mark. Fine changes in the brightness of the test pattern were brought about by an absorbing wedge.

The readings were taken in the following sequence: 1st, the observer was kept in the dark till completely adapted and was then shown the pattern for one second. The minimum illumination necessary to distinguish it was measured. 2nd, a white screen was put into position at which he gazed for five minutes. The light was turned on, giving a 'blinding' brightness of thirteen candles per sq. metre. 3rd, the light was turned off and the point fixated. The time for the test object to become visible was noted. 4th, the blinding was repeated with fifteen seconds' exposure and the time taken for discernment was measured as before.

His conclusions are that the limit of vision is very variable for different observers: it lies between 1 and 10 millionths of one candle per sq. metre. The form of the recovery curve from different times of blinding is roughly the same for all observers, there being two main types. The recovery is about three times more rapid for the short than for the long period of blinding. No correlation was found

between the ability to discriminate brightness and any adaptation factor.

Flügel (1921), using twenty-three observers, measured their visual acuity in daylight with Snellen types at 6 m.; their light sensitivity by the ability to recognize the illumination of a 30° white field in an otherwise darkened room; their visual acuity as measured by a keyhole-shaped test object, cut out of white paper and illuminated by a source of 0·1 and 0·2 C.P. The daylight visual acuity was first tested, and then the subject was brought to a constant level of light adaptation by gazing for two minutes at a large screen illuminated by a 1,000 C.P. lamp. After this the light sensitivity and the visual acuity were measured, 1, 10, 20, 30, 40, and 50 minutes after the large 1,000 C.P. lamp had been switched off and the observer was in darkness. All readings were binocular. The principal conclusions were: (1) That the results of two sets of readings taken by the same test at 40 and 50 minutes of dark adaptation show a high correlation. From this it is concluded that the results are reliable and that 40 minutes is a sufficiently long time in order to arrive at a knowledge of a person's capacity for night-vision. Fairly accurate measurements can be got at shorter intervals. (2) That visual acuity in daylight does not correlate significantly with light sensitivity at any adaptation level but correlates fairly well with visual acuity in dim light. (3) That light sensitivity tends to correlate slightly with visual acuity in a dim light. (4) That visual acuity in a dim light correlates only slightly with visual acuity in dim light of rather higher intensity. It is a pity that the actual results, illuminations, times, &c., are not more specifically stated.

Jones (1921) was concerned with the testing of night pilots for night-vision. Twelve observers were used, all officers in the Royal Air Force. The procedure was much the same as that employed by Flügel. The daylight acuity for Snellen's letters was measured, an auxiliary electric lamp being used one foot from the letters. After this the eyes were adapted for five minutes to the brightness of a large white screen illuminated by a 1,000 C.P. lamp. The light was switched off and readings were taken of the light sensitivity for the fovea and at 10, 20, 40, and 60 degrees from it. The visual acuity for Snellen's letters was also measured, the illumination being increased until 4 out of 4 could just be read. The readings were repeated every twelve minutes for three-quarters of an hour. It was found that individuals differ much in light sensitivity. The results for 20, 40, and 60 degrees to the periphery give the same ranking for light sensitivity as those at 10 degrees. Light sensitivity attains its maximum for vision in the neighbourhood of 20 degrees to the temporal side of the fovea. Dark adaptation for 16 to 20 minutes is sufficient for practical purposes for testing both the light sensitivity and the visual acuity of the dark-adapted eye. An individual's visual acuity in daylight or dim light is no criterion of his light sensitivity. Visual acuity in daylight correlates moderately with visual acuity in dim light. Illuminations and physical constants were carefully measured.

Other work on the subject has been done by *Nutting* (1916 *b*), see page 20, and *Korff-Petersen* (1919). *Downey* (1919) believes there

is no binocular summation in the dark-adapted eye and that dark adaptation of one eye has no effect on the other.

Hecht (1924) deals with the theoretical aspects of dark adaptation, such as the regeneration of visual purple. See p. 17.

Allen (1924 *a* and *c*) measured the apparent brightness of a white light during adaptation to different brightnesses for both eyes and also when the non-observing eye was kept blindfold. See p. 60.

2. Size of Pupil.

Uhthoff (1890) made an investigation into the size of the artificial pupil required to give maximum visual acuity data required for other of his researches. The sizes of diaphragms used ranged from 1·06 to 3·02 mm. diameter: the slit width was altered inversely as the area of the diaphragm in such a way as to get equal brightnesses of the retinal images. He found that with high illuminations the 2·06 mm. diaphragm was better than either the 3·02 or 1·55 mm. diaphragm, whereas at low illuminations the larger apertures gave increasingly better results. The investigations were conducted in coloured lights of wave-lengths 505 $m\mu$ and 605 $m\mu$. He attributed the results to diffraction, since with 1 mm. pupils the limbs of the test object appeared indistinct and broad. He concluded that a 2·05 mm. diameter pupil gives optimal results and is the best to use in general; above this diameter the optical irregularities of the eye come greatly into evidence.

Hummelsheim (1898) effected alterations in the pupillary aperture by homatropine and pilocarpine. He determined the visual acuity by Snellen's prong under different degrees of daylight illumination varying from 1 to 200 mk. (measured by the Weber Photometer). The result obtained was that visual acuity improved progressively the smaller the pupil, the smallest used being 1·5 mm. The differences tended to be less marked at lower illuminations.

Other early workers were Bordier, Broca (1901–3), and *Lister* (1913); see Parsons (1914 *b*).

Cobb (1915) used a 3·5 cm. Ives test object viewed at a distance of 125 cm. by one eye through artificial pupils of diameters 1·0, 1·4, 2·0, 2·8, 4·0, 5·6 mm. The latter were placed as close to the eye as possible (1·5 cm.) and were centred by causing the image of the test object to occupy the centre of the diffuse outline of the aperture. By flashlight photography it was shown that the real pupil was always considerably larger in diameter than the artificial pupil.

The procedure was to put the largest artificial pupil in front of the eye and then to ask the subject to alter the adjustment of the test object so that the lines of its pattern were just visible. A continuous record on a moving drum was taken of his judgements for one minute, when the pupil was changed for the size smaller and the performance repeated for each in turn, after which a reverse series was taken. The brightness was kept constant either at 189 or 5·9 candles per sq. metre, or was altered so as to give an equally bright retinal image for each size of pupil. His results are given in Table VII (mean of three observers).

TABLE VII.

Size of Artificial Pupil in mm. diam.	Visual Acuity with brightness adjusted so as to give equally bright images on the retina.	Visual Acuity at constant brightness of test surface. 189 $C/_{m}^{2}$.	5·9 $C/_{m}^{2}$.
1	3·98	4·03	3·52
1·4	5·03	5·32	4·44
2	6·05	6·63	5·24
2·8	6·04	7·07	6·00
4	6·06	7·18	6·09
5·6	5·79	6·87	5·73

He finds that the maximum resolving power of 2·16 minutes is smaller than that given by the formula $\theta = 1{\cdot}22\ \frac{\lambda}{D}$, which is 2·39 min. where λ, the wave-length, was taken as 0·00057 mm., the value for the brightest part of the spectrum, and D is diameter of the aperture. It should be noted that the formula applies to the resolution of two points and that D is optical aperture of the system in question. Further conclusions are that there is an optimum visual acuity for a size of artificial pupil somewhere between 1 and 5·6 mm. diameter. Also that when the brightness of the retinal image is compensated the maximal visual acuity is obtained with a smaller pupil than in other cases. Refractive errors are more marked with large apertures.

Blanchard (1918) measured the pupillary aperture when the eye was directed towards surfaces of from 1,000 to 1×10^{-6} millilamberts brightness. He employed the flashlight photography method. The diameter of the pupil varied from 7 to 2 mm. If one eye only was employed, the other being kept shut, the diameters were slightly increased for all but maximal and minimal apertures. *French* (1919) gives a formula for the area of the pupil (A) for different intensities of stimuli (I): $A = K\, I^{1/5}$, where K is a constant.

Nutting (1916 *b*) measured the pupillary aperture at different brightnesses. The method was to place a slender brass wedge in front of the eye and to move it up and down until the umbra from each edge just reached the middle line (the line of sight). This point was read on the graduations of the wedge. The results are given in Table VIII.

TABLE VIII.

Brightness (log ml's).	−5	−4	−3	−2	−1	0	1	2	3
Diam. of pupil in mm.	6·9	5·8	5·0	4·3	3·8	3·3	2·9	2·5	2·2

Reeves (1918 *a*), working at the Eastman Kodak Research Laboratory, followed the course of pupillary contraction and dilatation by taking motion pictures. Eight subjects were used and eight brightnesses ranging between darkness and white paper in bright sunlight. Each range was studied separately. The rate of contraction was recorded by a continuous picture and the rate of dilatation by single flashes at different times after the removal of the stimulus. The average pupil closes to its minimum in five seconds, but takes a time varying between three and ten minutes to open to its maximal diameter. The results are given in Table IX.

TABLE IX.

Rate of Closing of Pupil.		*Rate of Opening of Pupil.*	
Time in secs.	*Diameter in mm.*	*Time in secs.*	*Diameter in mm.*
0	8·1	0	2·8
0·1	7·9	0·5	3·1
0·2	7·7	1·0	3·5
0·3	7·4	1·5	3·9
0·4	7·0	3·0	4·7
1·0	5·5	5·0	5·5
2·0	4·0	15·0	6·5
3·0	3·5	60·0	7·2
5·0	3·2	300·0	7·6

Tables were also given for the pupillary diameters of their subjects at various levels of brightness adaptation when both eyes and one eye only were used. Other results of the Kodak Laboratory on similar subjects are given by *Reeves* (1917 *a*) and *Hunger* (1917), see also *Laurens* (1923). *Rich* (1923) discusses *Ferree* and *Rand's* results (1923), p. 9, on visual acuity at low illuminations and points out that they can be explained by variations in pupillary aperture.

THE INFLUENCE OF LATERAL ILLUMINATION, INCLUDING 'GLARE', ON VISUAL JUDGEMENTS

1. Standard Test Objects, Threshold Values, Contrast and Maximum Tolerable.

The problems in connexion with the influence of lateral illumination on visual acuity have been stated by *Parsons* (1914 *c*) as follows: 'The disagreeable effects of a bright light in the field of vision are familiar to every one, but the cause of the distress, and how far it is seriously deleterious to the eye, have proved difficult to discover. Theoretically various factors come into play, such as alterations in the size of the pupil, alterations in contrast (spatial induction), and fatigue. As regards contrast, if the light source is screened from the test object, but not from the eyes, the illumination and the objective contrast between the object and the background remain unchanged. Subjectively, however, the conditions are altered. Owing to the oblique incidence of the lateral light, the media of the eye are flooded with light, partly transmitted through the sclerotic as well as through the refractive media, and partly reflected from the various refracting surfaces, and thus unequally distributed. The conditions are complex and it is scarcely possible to foretell the effects.'

The paper contains a detailed review of the work on the subject up to 1914, when Cobb had published his early papers.

It had been shown that the perception of detail by the eye might be improved if the eye were not completely screened from lateral illumination. Sewall (1884) found, for instance, that he could see fine lines ruled on a card better when the light of the sky was allowed to fall on the eye than when it was not. This seemed not to be due to a diminished size of the pupil, since it was shown by

Schmidt-Rimpler (1887) that after dilatation of the pupil by atropine he obtained an increased acuity when the filament of an electric lamp was focused on the sclera. When the illumination, however, was above a certain value he got diminished visual acuity.

Uhthoff (1885) and Depène (1900) got different results. They found that when an object was illuminated to about five foot-candles or more, and when the value of the visual acuity was 1·25, there was increased visual acuity when the eye was laterally illuminated. This increase did not occur when the pupil was dilated by atropine. At lower illuminations of the test object there was progressively diminished visual acuity, and it could be diminished still farther by decreasing the angle between the lateral source and the line of vision, by increasing the intensity of the lateral source, or by increasing the size of the retinal image. Depène attributed the results to changes in retinal adaptation.

Hummelsheim (1900) found a progressive rise in visual acuity when a large grey field surrounding the test object was illuminated to 0–200 metre-candles, and that this rise in visual acuity was diminished but not abolished by atropine. Other workers were *Borschke* (1904), Heymans (1901), and Tschemolossoff (1904); for details and references *Parson's* paper should be consulted.

The most important papers of recent years are those of *Cobb* in America. His first investigations (1911) were conducted with the Ives test object, and for a lateral illumination a light attached to the arm of a Wundt perimeter. His conclusions were as follows: (1) The vision of an object is lowered progressively as the lateral source of light becomes brighter and the angle formed by it and the line of vision is decreased. (2) If the test object is very bright, lateral illumination may cause increased visual acuity. (3) When the light is at 10° from the line of vision and the lateral illumination of the eye and the illumination of the test object are equal, there is no appreciable reduction of acuity at any intensity. (4) The presence of the retinal image of the lateral source is a negligible factor in the depression of vision; diffusion and reflection from the eye media are the important factors, since it still occurs when the image falls on the blind spot. (5) The effects of a lateral source of light can be imitated by throwing a haze of light over the central retina and test object.

'The differences in results just quoted must be due to changes in the sensibility of the part of the retina concerned in vision of the object, induced by scattered light in the case of lateral illumination, falling on the retina not on but about that part, and probably not farther away from it than 15° measured in the visual field (the remoteness of the blind spot)' (*Parsons*, 1914 *c*); and later, 'The unpleasant feeling of dazzling (*Blendung*) and the disturbance of vision produced by dazzling are totally different things, and need by no means necessarily recur to the same extent at any given time'.

The complexity of the problems involved in investigating the effects of lateral illumination on visual acuity as revealed by the usual tests on black and white objects has compelled workers to investigate certain other factors. Of these may be mentioned the influence of different levels of dark adaptation, of pupillary diameter,

and of contrast on visual acuity, &c. These are for the most part dealt with in other places; only those aspects of them having a direct bearing on the subject of lateral illumination will be dealt with here. The just perceptible difference of brightness, the difference of threshold, or the contrast sensibility of the eye, as it is variously called, has been much investigated, since it is of considerable theoretical as well as practical importance (*Hartridge*, 1922). It is only lately that the influence on it of lateral illumination has received attention, and most of this work has been in conjunction with the influence of lateral illumination on the threshold value; the two will be considered together, and also other work on the visual acuity for test types, &c.

Hess and *Pretori* (1894) investigated the influence on the apparent brightness of a spot exerted by a surrounding field. It was found that the physical brightness of the spot had to be increased a certain definite fraction of the increase in brightness of its surroundings in order that it should remain apparently equal in brightness to a second spot in constant surroundings. The work did not touch on the question of the modification of visibility for detail or the alteration of the difference threshold by changes in the brightness of the surroundings. *Hess* (1920) found that an original brightness pattern with a contrast of 1 to 800 can be rendered invisible by the action of a very bright surrounding field. The brightnesses are not stated. There is a full account of the apparatus.

Cobb (1913–20) and *Cobb* and *Geissler* (1913) continued their researches, this time illuminating the whole of the peripheral field of vision by means of a box painted white inside and approximating to a sphere in shape. Two holes were cut at opposite points of the box and through these the observer looked at the test object 200 cm. away. The inside of the box was illuminated through a milk-glass window immediately above the observer's head. They measured the visual acuity of the eye and its power to discriminate small differences of brightness both during light adaptation (the peripheral field illuminated) and dark adaptation. In the experiments on the discrimination of small differences of brightness the surrounding field had a brightness of 41·9 candles per square metre in the early experiments, and of 2·87 candles per square metre in the later ones. The test field had a brightness variable from 0·001 to 100 candles per square metre. A standard time of exposure of three seconds was employed in all cases. The results showed marked individual variations, but in general the effect of peripheral illumination was the same in general direction for all subjects, namely: (1) When the illumination of the peripheral retina was high and of the test field low, there was diminished visual acuity and discrimination of brightness differences. (2) When the surrounding field was slightly brighter than the test object, visual discrimination was found to be actually better for both observers and by both criteria than for a physically identical object seen in dark surroundings. (3) 'Surroundings of a brightness about equal to or less than that of the test object show no consistently better or worse results than dark surroundings with the identical test object. On the whole, visual acuity under these circumstances was slightly improved and the difference limen increased.' In commenting on the different shapes of the curves for visual acuity and difference threshold they say,

'Comparison of the visual acuity and brightness-difference curves under parallel conditions shows that as the test-object brightness is reduced, the difference limen, usually at a fairly definite point, takes rather an abrupt rise. Visual acuity, on the other hand, while always showing a slight progressive diminution beginning at the very highest brightness under a similar change of conditions, never undergoes such rapid decrease as differential sensibility. This fact is to be considered in connexion with the almost obvious fact that discrimination of fine detail depends upon (*a*) a physically perfect image on the retina, and (*b*) probably upon the accurate fixity of this image, which in turn depends on the steadiness of the extra-ocular muscles. Since there is nothing in uniformly bright or dark surroundings to influence either of these factors' (except pupillary aperture) 'it may be concluded that visual acuity depends mainly upon these, and hence varies less under the influence of contrast than does differential sensitivity, because the retinal image is always equally perfect. . . . As contrasted with visual acuity, differential sensibility can be said to depend mainly on retinal conditions, and to a very minor degree upon the perfectness of the retinal image.'

Cobb (1916 *b*) described a new apparatus for investigating the effect of bright surroundings on the difference threshold. He aimed at getting the two halves of the field at the same illumination, with the difference across the line of contact uniform along its whole length. The earlier apparatus was probably defective in these respects, and in addition there was no means of knowing when the difference was zero (physically). The new method is additive, that is, to one half of an evenly illuminated field a small brightness is added. Normally the latter was 8 per cent. of the constant field, but it could be reduced by a rotating disk. An image of this brightness-difference pattern was formed at one of the openings of the box used in previous experiments (1913). The opening was 3·4 × 3·6 cm. Brightnesses were measured by the Bechstein portable photometer. Precautions were taken to keep the illuminations constant.

Two procedures were employed (1916 *c*) for obtaining the difference threshold: (1) The surroundings were kept at the same brightness and the brightness of the test field was varied, and (2) vice versa. The differences in brightness between the two halves of the field were made in twelve steps of one unit each. The magnitude of each step had to be changed in the course of the experiments because the observers showed a marked practice effect. The results were analysed by a method founded on Gauss's law of error: for each set of observations there was given one value 'corresponding to the appearance of greater brightness on the left half of the field and one on the right. For each of these it was possible to work out a measure of "diffusion" in the form of probable error.' Five hundred observations were made on each of the three subjects. The results are given in Table X.

TABLE X.

Brightness in Candles per square metre.		*Fractional Values of the threshold difference.*	
Field.	*Surroundings.*	*Difference Threshold expressed as per cent. of field brightness.*	*Diffusion expressed as per cent. of field brightness.*
436	17.3	0.45	0.60
128	17·3	0·35	0.54
35.3	17.3	0·32	0.54
17.6	17.3	0·27	0.49
8·92	17·3	0·45	0.67
2.11	17·3	0.74	1.34
0·540	17.3	2.71	3.57
0.0	17.3	0.00	—
17·5	12.1	0.73	1.12
17.6	46.0	0.38	0.67
(17.6)	(17.3)	(0.27)	(0.49)
17.6	8·64	0·33	0·55
17·6	2.15	0.39	0.61
17.6	0.547	0.39	0.71
17.6	0.0	0.46	0·76

One curious result was obtained, namely that the threshold when the left field was the brighter was twice as large as that for the right field. Cobb discusses this in detail and comes to the conclusion that it must be due to a 'space error'.

His main conclusions are: (1) When either the brightness of the surroundings or that of the test field 'is raised above the point of equality the threshold increases and does so almost as a linear function of the variable brightness condition, as would be expected in the case of change in the field brightness, from Weber's Law. However, the surroundings are far less effective in bringing about a threshold increase than is the brightness added to the test field itself.' For one unit of brightness added to the field, the threshold increases on the average 0·0035 units, while for a similar increase in brightness of the surroundings the threshold increases only 0·00085 units, or about a quarter as much. The threshold assumes a minimal value at or near the point of parity of field and surroundings. A graph is given showing the deviation from Weber's Law (applied to the field) as the brightness of the surrounds is altered. (2) 'The changes in the sensitivity of the eye due to various brightness conditions, when established by the value of the fractional threshold, are seen to be predominantly dependent on the ratio that exists between the field brightness and that of the surroundings. As this ratio drops below unity the threshold increases rapidly to a large extent. As the ratio rises above unity the threshold rises, but slowly and to a small extent. Improvement with practice is more pronounced in the former case.' (3) The mean variation tended to be larger in cases where the surround was brighter than the field.

Nutting (1916 *a* and *c*) measured the 'Discrimination Factor' and 'Threshold Limit'. The term 'discrimination factor' 'is defined as the field brightness divided by the just noticeable difference, B/dB. This quantity is a direct measure of the power to distinguish details except when large colour differences are present. Visual acuity so called, a mere sharpness of definition, is a minor factor when contrasts are slight.' To measure the threshold limit 'the eye was sensitized in each case to a certain brightness by viewing a white field illuminated to

the proper amount. This field was 60 cm. square, and viewed from a distance of 35 cm., and was illuminated to brightnesses ranging from 0·000001 millilamberts to 2,000 millilamberts. After sensitizing, the light was switched off, and an attempt made to see a small square (30 mm. square) in the centre of the large square field, illuminated from behind. The brightness of this small square was adjusted until it could just be seen at the instant of switching off the brighter field.' For the glare data the brightness of the central patch was increased until it just appeared uncomfortably bright with the eye adapted to the given brightness of the surrounding field. These results can be expressed as the equation $G = 1700\,B^{0\cdot 32}$, where G is the glare value and B is the brightness to which the eye is adapted. The figures give support to the suggestion that the ratio of brightness met with in ordinary interiors should preferably not exceed 100 : 1, but this ratio may safely be exceeded considerably at very low illuminations. The results are quoted in Table XI, and are plotted in the paper of 1917, where there also occur figures showing the time required for the eye to adapt itself to perceive a threshold stimulus after exposure to 0·1, 1·0, 10, and 100 millilamberts. There are also some results for adaptation to coloured lights. The bearing on illumination problems is discussed. (See also p. 20.)

TABLE XI.

Field Brightnesses in millilamberts.	*Difference Fraction.*	*Discrimination Factor: the reciprocal of Diff. Fraction.*	*Threshold Limit, in millilamberts.*	*Glare Limit in millilamberts.*
0·000001	(1·00)	1.0	0·00000093	20·1
0·00001	(0·66)	1.5	0.0000042	40.7
0·0001	0·395	2·5	0·000019	89·0
0·001	0·204	4·5	0·000087	186·0
0·01	0·078	12·8	0·00039	400.0
0·1	0·037	27·0	0·00174	810.0
1.0	0.0208	48·2	0·0081	$1{\cdot}66 \times 10^3$
10·0	0·0174	57.5	0·036	$3{\cdot}42 \times 10^3$
100.0	0·0172	58·1	0.28	$7{\cdot}25 \times 10^3$
1000·0	0·0240	41.7	2·15	$14{\cdot}45 \times 10^3$
10000·0	(0.048)	20·9	(232.0)	$30{\cdot}90 \times 10^3$

Blanchard (1918) measured the threshold, contrast, and glare sensibilities of the eye for different field brightnesses. The threshold sensibility is defined as the reciprocal of the least perceptible brightness instantaneously substituted for that at which sensibility is desired. The contrast sensibility is defined as the reciprocal of the least perceptible difference in brightness between two adjacent fields under the same conditions. The glare sensibility is defined as that brightness which just appears glaring to an eye previously adapted to any field brightness. He used a large field which could be illuminated with brightnesses of 10^{-7} to 10^3 millilamberts. The observer sat at a distance of 35 cm. from a test surface 3 cm. square which was situated in the centre of the screen and which subtended an angle of five degrees. In the case of the threshold sensibility coloured light was also used. The illumination was regulated by means of a wedge.

The results are expressed as an equation :

$$\frac{T}{B} = \left(\frac{B}{B_0}\right)^{n} \text{ or } \log T = (1-n) \log B + n \log B_0,$$

where T = test-spot threshold for any given brightness of field (B), B_0 = absolute field threshold (0·00000071 ml.), n = a constant for any one colour.

The curves relating B and T are straight lines between 100 and 2,000 ml.; over this range there is a condition similar to the Weber-Fechner law, while beyond it the ratio rises again and at blinding intensities it would approach unity, that is, the instantaneous threshold would be equal to the sensitizing field itself just as at the other end of the curve.

For the measurement of contrast sensibility he used a test square the top half of which was covered by a wedge of grey gelatine. The eye was adapted to the sensitizing field brightness and the wedge was moved so as to give a just perceptible difference. The values obtained are those of 'Fechner's Fraction' at different stages of adaptation. He also measured the ability of the eye to appreciate contrast at varying time intervals after switching on the field which had a brightness of 0·1 ml. Contrasts of 0·97, 0·87, 0·67, 0·39, and 0 were employed. It was found that the eye adapted itself to the brightness in a few seconds when a maximal ability to discriminate contrast was obtained in all but very big contrasts, which took longer. The values of the 'Fechner Fraction' are plotted against the field brightness. Blanchard's values are similar to those of König after the eye had been light adapted for one minute. He gives an interesting graph showing the relation between the threshold brightness, least perceptible difference, and glare value for different strengths of field brightness.

The method of obtaining the glare sensibility was to adapt the eye to different brightnesses and then to switch on suddenly a very bright field of 4°. The observer judged whether it was glaring or not. The relation is given by $G = cB^n$, where G is the value of the glaring brightness, B is the adaptation brightness, and c and n are constants. The original paper should be consulted.

Schjelderup (1920) modifies Weber's formula to $\Delta i = ai + bI$, where i is the intensity of the test-field stimulus, I that of the surrounding field, and a and b are constants. When i is greater than I Weber's Law holds approximately, but when I is greater than i it breaks down seriously. In the latter case, and with fields less than 1°, the difference threshold may become independent of the test-field intensity and proportional to that of the surrounding field.

Dittmers (1920) conducted similar experiments. As a surrounding field she used papers of different shades of grey. The diameter of this field was 20 cm. The test field was 3·7 cm. diameter and was lighted by means of gas-filled lamps. On to this test field a slit image was projected, the intensity being varied by means of an episcotister. The direction of the image could be altered. The illumination was increased from a reading below the threshold and the observer had to judge when the image on the test field just became visible. The difference threshold was at a minimum when the two fields were equally bright. *Seffers* (1922) did similar work.

Bell, Troland, and *Verhöff* (1922) in the Report of the Sub-Committee on Glare of the Research Committee of the Illuminating Engineering Society defined glare as 'the sensation produced by light so invading the eye as to inhibit distinct vision'. They classified the

various forms of glare into: (1) 'Veiling Glare. Light somewhat uniformly superimposed on the retinal image, thus reducing contrasts and hence the visibility.' They compare it to the fogging of a photographic plate. It is experienced when reading under an open sky. (2) 'Dazzle Glare is produced by adventitious light so refracted and scattered as not to form part of the retinal image.' (3) 'Scotomatic Glare is produced by light of intensity such as to fatigue the retinal sensitivity to below the concurrent limit for visual images.' It corresponds to cases of heavy over-exposure in photography.

In their investigations they used a test target of 45 × 48 in., in the middle of which was a perforation of 1·5 in. diameter. The target was covered with cardboard, having a coefficient of reflection of 0·74. The distance of the observer was 25 ft. On the target black paper letters were pasted on circles whose circumference subtended 1, 2, 3, and 4 degrees to the observers. Two letters were employed, a 'C' whose size gave a visual acuity of 20/20 at 25 ft. and an 'E' of double the size.

For the production of veiling glare the target was viewed through a box, painted black inside and with 2-in. diameter holes cut back and front. At an angle of 45° across the line of sight was placed a lantern slide plate illuminated through a hole in the side of the box: this produced a veiling glare. An illumination of 0·6 foot-candles on the target rendered the 'C' just visible. The illuminations used to produce the veiling glare and the consequent reduction of contrast are not clear. Small amounts of veiling glare were said to produce very little loss of acuity or discomfort. The 'extinguishing value' of veiling glare is obtained when the fraction $\frac{B_c}{B_s + B_g}$ is greater than 0·02, where B_c, B_s, B_g are the brightnesses of the object, surrounding surface, and veiling glare respectively.

In the work on veiling glare they employed illuminations such that 'the target as a whole emitted in the direction of observation 0·003 C.P. per square inch for each foot-candle of illumination, which is equivalent to 5·8 millilamberts'. Similarly each 100 C.P. in the glare lamp behind the aperture gave a brightness of 110 millilamberts. Their results are given in Table XII.

TABLE XII.

Illumination on Screen in fcs.	*C.P. of glare lamp.*	*Dazzle Area.*	*Result.*
2·25	50	1°	Letters on 1° circle not easily read.
2·25	200	?	„ „ 2° „ „ „ „
			„ „ 1° „ „ read at all.
0·05	200	more than 2°	„ „ 2° „ obliterated.
			„ „ 3° „ impaired.
0·3	200	5°	„ „ 4° „ „
5·9	200	1°	"C's" „ 1° „ just invisible.
			"E's" „ 4° „ „ visible.
2·0	500	5°	Circle of legibility = 3°.
7·5	500		All clear except 1° circle.
6·5	15000	10°	Everything obliterated.

The conclusions were that dazzle glare is the most serious in that it interferes most with reading and other ocular functions. It is also found most often.

Ambronn and *Geffcken* (1921) investigated glare by a tachistoscopic method.

Luckiesh and *Holladay* (1925) investigated the factor of irradiation in addition to veiling glare, dazzle glare, and blinding glare. Irradiation is an experience of everyday life: it is well known that fine black lines on a white ground appear smaller than white lines of a similar thickness on a black ground. The effect is due to the great diffusion of the light from the retinal image in the former case. Printed characters on ordinary white paper appear to be much finer than they really are, and if the illumination of a page of printing is very materially decreased by looking at it through a pin-hole in a black disk the letters appear much nearer their real thickness (*Rivers*, 1896).

For their work on irradiation Luckiesh and Holladay employed a large cardboard screen in the centre of which a circular hole was cut which could be illuminated from behind by a lamp. In this opening was placed an opaque annulus whose outside diameter (34 mm.) was smaller than the opening, and which had a variable inside diameter. The observer was at a distance of 344 cm. A card of the same material as the large screen was interposed between the annulus and the large screen, and the observer was adapted to this brightness. The card was then withdrawn suddenly and the illumination of the hole necessary to render the opaque annulus just invisible was measured. Curves are given for this value for brightnesses of the surrounding field (F) of $\frac{1}{10}$, 1, 10, 100, 1,000 millilamberts. The results can be expressed in the formula $A = 10{\cdot}7 \log B_2 - 2{\cdot}07 \log F - 37{\cdot}4$, where A is the visual angle subtended by the rim of the annulus and B_2 is the brightness of the light shining through the hole.

For veiling glare they employed an annulus of grey paper with an inside diameter of 2 cm. and a variable outside diameter. This was pasted on to a large screen of variable brightness. The observer viewed the annulus through a glass plate inclined at an angle of 45° to the line of vision, and illuminated by a bright diffusing glass placed so that a certain amount of light was reflected into the observer's eyes. The visibility factor is defined as (brightness of background ÷ (difference of brightness between test object and background), or, taking into account the reflection factor of the material used, $\dfrac{0{\cdot}9\,F + B_1}{0{\cdot}9\,F\,\dfrac{f_1 - f}{f_1}} = V =$ visibility factor, where $F =$ brightness (actual) of background; $B_1 =$ veiling glare (from the glass plate); $f =$ reflection factor of test object; $f_1 =$ reflection factor of background; $0{\cdot}9 =$ transmission factor of glass.

It was found that the test object was just visible when $V = M(d - 0{\cdot}5)^{0{\cdot}4}$, where M is a constant whose value is between 40 and 50, and d is the visual angle subtended by the solid rim of the annulus. A graph of the results is given. In a test where the visual angle was kept constant at five minutes, the visibility factor is:

1·0 for maximum clearness of vision.
3·5 „ practically unimpaired vision.
66·0 „ practically the limit of visibility.
85·0 „ the extreme limit of visibility.

It should be noted that the condition of affairs with a small visibility factor is similar to that which obtains with small black and white objects: large variations of brightness have but a small effect on the minimum visual angle. When the contrast between test object and background is smaller and the visibility factor is large in consequence, small differences of brightness effect large differences in the minimum visual angle visible. This result is in accordance with Cobb's reasoning (1914).

Dazzle glare was investigated by the same arrangement as veiling glare, except that the glass plate was removed and a lamp to produce the dazzle shining directly into the eye was substituted. The size of the diaphragm in front of the dazzle lamp could be varied and also the angle from which it shone into the eye. The formula given for the visibility factor, V, is $V = \dfrac{F + 4\dfrac{E}{D^2}}{F\dfrac{f_1 - f}{f_1}}$, where the symbols are the same as for veiling glare, E is the illumination produced at the eye of the observer, and D is the angle made by the dazzle lamp with the line of sight. The factor $\dfrac{4E}{D^2}$ is equivalent to a veiling brightness of B_1 in millilamberts. A graph is plotted showing the relation between a veiling brightness producing the same decrease in visibility as a dazzle-glare source at various angles D above the line of vision and this angle. From the formula it is apparent that equal amounts of dazzle glare are produced by a 100-watt lamp at 10°, a 225-watt lamp at 15°, and a 900-watt lamp at 30° above the line of vision. Glare practically ceases at angles greater than 30°.

For the investigation on blinding glare the observer sat in front of a uniformly lighted screen in which was an opening variable in size from 1·8 to 30·5 cm. The observing distance was 244 cm. The observer judged when the illumination through this hole was of just 'blinding intensity'. The relation was found to be a simple one, log $B = 3{\cdot}3 + 0{\cdot}3 \log F$, where B is the brightness of the blinding-glare source (10^3 to 10^4 millilamberts) and F is the field brightness (0 to 10^2 millilamberts).

Bordoni (1924) employed the contrast sensibility of the retina for investigating the phenomenon of glare. He expressed the results as 'coefficients of perceptibility' (the 'discrimination factor' of Nutting). The procedure was to adapt the eye to certain levels of light adaptation ranging from 0·025 to 10 millilamberts, and then to measure the just appreciable difference of brightness on the two sides of a paper-covered prism which was placed in front of the adaptation screen. This screen had an aperture cut in it, through which shone the source of light whose properties were to be investigated. The essential part of the research consisted in the comparison of the glare-producing effects of sources of light having different intrinsic brightnesses (2 to 1,000 lamberts). The latter were obtained by the use of plain, frosted, and opal gas-filled lamps. Bordoni does not appear to have made a control experiment of the contrast sensibility of the retina without a glaring source in the field of vision. The chief conclusions are: (1) that the

phenomenon of glare is continuous, appearing at low intensities of the glaring source. (2) That it is not the intrinsic brightness, but the luminous intensity of the source which is the important factor in the production of glare; the disability produced by a frosted lamp is practically the same as that produced by a clear lamp of equal candle-power, although in some cases the frosted light is somewhat better. With two sources of equal intrinsic brightness the one with the larger area produces the most disability. (3) That two sources with not widely different areas will produce the same amount of disability if the illumination at the eye in each case is the same. The latter varied from 1 to 100 lux. This was shown by placing the sources of light at different distances from the eye. (4) That the initial level of light adaptation has a comparatively small effect on the amount of disability produced by any given source of light. All these results are based on determinations where the source of light was at an angle of six degrees with the test surface. As a result of them it is stated that a source of light becomes glaring when the coefficient of perceptibility reaches ten. This is an extremely low value: under the best conditions the coefficient is equal to 150·0. The value of ten is obtained, for instance, when the glaring source has a luminous intensity of 0·45 candles and is at a distance of 0·85 m. from the eye. The disability produced by a point source of light is of the same order as that produced by an adaptation level of the same value. Another series of experiments was conducted with the glaring source at different angles (6–35°) with the line of vision. As a result of this it is found that all sources of light should be at an angle of more than thirty degrees with the line of vision. The final conclusion is that in order that a matt shade to a lamp may be efficient it should have a very considerable area. The paper abounds in diagrams, but unfortunately the results on which they are based are not quoted.

Papers discussing glare and allied topics without bringing forward any new experimental evidence are *Clarke* (1915), *Kerr* (1917), *Bayliss* (1918), *Caldwell* (1923), *Maisel* (1924), *Pelle* (1924), Jones, Miles (1923), *Teichmüller* (1925). *Harrison* (1920) gives some useful measurements.

2. Theoretical.

Very few attempts have been made to correlate the findings on glare with underlying retinal mechanisms. *Cobb* (1916 *c*) assumes that when light falls on the retina, a photo-chemical substance S is broken down into two other substances W and B, and that they reunite in darkness to re-form S. This is represented by $S \underset{\text{dark}}{\overset{\text{light}}{\rightleftarrows}} W+B$, where S is the amount of the substance originally present and W and B the amounts of the break-down products. It is assumed that B is diffusible throughout the retina. The rate of break-down at any point is proportional to L_1, the amount of light flux, and the amount of original substance $(S-W_1)$ present at the point considered, i.e. $L_1\,(S-W_1) = W_1 B$. For the surrounding retina $L_2\,(S-W_2) = W_2 B$. If K is the ratio of the distribution of the substance B between the two points, $B = KW_1 + (1-K)\ W_2$. Also if L_2 is small, then W_2 is

small, and B approaches KW_1 in value. Substituting L_1 $(S - W_1) = KW_1^2$, if L_2 is large, L_1 $(S - W_1) = W_1C$, where C is a constant. Assuming that a constant increment of W is the condition of a threshold difference in sensation [see *Hecht* (1924)], the fractional threshold is a minimum when $W = \frac{1}{2}$ S and $L = B$. This reasoning is extended by *Adams* and *Cobb* (1922): 'with a few simple . . . assumptions as to the nature of the nerve processes of the retina' it has been possible 'to derive a theoretical expression for the variation of difference threshold'. They assume that the response of a fibre of the optic nerve consists of a series of impulses whose frequency increases with the brightness of the corresponding part of the field, and also that the time of the relative refractory period varies inversely with the brightness at the corresponding part of the field. Equal differences in frequency are equally perceptible. (*Verworn* has shown that the electric impulses in the optic nerve are discrete.) The reasoning cannot be stated briefly; the original paper should be consulted. Their final equation is $\frac{\Delta B}{B} = \left(\frac{B}{B_1} + 2 + \frac{B_1}{B}\right) \Delta S$, where B and B_1 are the respective brightnesses of the test field and surrounds, ΔB is a just perceptible increment in brightness, and ΔS is a just perceptible increment in the rate of nervous impulses. The results when plotted (to suitable scales) certainly agree remarkably well with the experimental results.

THE SPEED OF RETINAL IMPRESSION

(with special reference to telegraphic signalling and to lateral illumination).

It has been seen that the functions of the visual-receptor apparatus are analysed only incompletely by the routine visual-acuity tests (page 29). The perception of small differences of brightness, for instance, involves factors which are not evident in the perception of black and white objects. In their efforts to analyse still further the functions of the eye, workers have been led to investigate the minimum time required for the perception of stimuli reaching the eye. The subject has considerable practical interest in relation to code signalling and other considerations pertaining to the services.

The minimum light flux visible to the eye is a function of four variables: duration, size, and brightness of the stimulus, and the previous history and environment of the eye. It is proposed to deal shortly with the first three factors, before passing on to a consideration of the fourth. If the duration of stimulus is long, the size of the object small, and the eye is completely dark adapted, one is in a position to determine the minimum luminosity perceptible to the eye. It should be noted that one cannot derive directly from this the minimum energy required to stimulate the eye.

The minimum radiation visually perceptible has been estimated by several observers: Wien (1903), Eyster (1906), Boswell (1907), Ives (1916 *a*), Buisson (1917), Russell (1917), Reeves (1917 *b*), and many others.

Of interest in this connexion is the apparent disappearance of stimuli of feeble illumination, apart from the 'night-blindness' of the fovea (see page 60).

Asher (1897) found that the amount of energy as light to give perception of a small area is constant, i. e. the product of brightness and angular area is constant provided that the diameter is not greater than two minutes. See also Riccò (1877) and Loeser (1905 *a*). *Charpentier* (1890) found that for exposures of not more than 1/8 of a second the product of time of stimulus and the threshold brightness is constant. For his work on the angular area and threshold brightness see Parsons (1914 *a*). *v. Kries* (1907) showed that for a given state of adaptation of the eye the product of the brightness, angular extent, and duration of stimulus is constant within limits. *Piéron* (1920) found that for very short exposures (less than 5 σ), in order to stimulate the eye, the brightness must be increased more than inversely as the time when the latter is reduced. See also *Blondel* and *Rey* (1924). Brückner and Kirsch (1911) did similar work on the chromatic action-time. In this connexion the rate of growth of the visual sensations is important. See *Luckiesh* (1914 and 1924). *Basler* (1912) was concerned chiefly with military signalling. He measured the shortest perceptible dark interval between two flashes. *Reeves* (1918 *c*) was concerned with the energy and brightness required for the absolute threshold with stimulus fields of various angular shapes and sizes. The observing eye was fairly completely dark adapted. For a square stimulus field of 1 sq. mm. viewed at three metres the total energy for threshold stimulation is $17{\cdot}1 \times 10^{-10}$ ergs per second; for a square of 144 sq. cm. viewed at 35 cm. the total threshold energy is 564×10^{-10} ergs per sec. and various intermediate values. The threshold brightness varied from 0·0072 millilamberts for the smallest field to 0·000000175 millilamberts for the largest. The average time to produce a just noticeable stimulus was 2·2 secs. *Dunlap* (1915 *b*) also measured the shortest perceptible time interval between two short flashes of light. He found the determinations difficult, almost impossible, because the first flash, when exhibited alone, is often seen as two successive flashes. The threshold light interruption appears to increase with increased duration of the first flash. For certain levels of light adaptation he found that the threshold for the light pause is lower in the light- than in the dark-adapted eye. *Forsythe* (1919, 1920) was directly concerned with speeds in telegraphic light signalling. He found the best time ratio for dot, dash, space to be 1 : 4 : 3. At a distance of 2,700 yards the minimal time for a 4-part signal is about 1·6 seconds, both in daylight and at night. Some observers appear to do slightly better in daylight. *Gildemeister* (1914) found that the just perceptible interruption of an otherwise continuous light flux is briefer as the brightness of the light is increased, but the amount of light so subtracted during a threshold interruption increases slowly with the intensity of the light. In his investigations on flicker photometry Porter found that the period during which a visual sensation remains undiminished appears to decrease as the time of stimulation increases, and within narrow limits one of these quantities is nearly inversely proportional to the other. The Ferry-Porter law

states that the speed at which a half-white, half-black disk must be rotated for flicker to disappear varies as the logarithm of the intensity of illumination of the white disk.

Rutenburg (1914), in a very complete paper, compared the threshold times for a light pause and a light flash. He used a field of fifty-six minutes' visual angle and gave his subjects ten to fifteen minutes' dark adaptation. For an equal duration of flash and pause it was necessary to have two to five times the illumination in the light–dark-light series than in the dark–light-dark series. In other words, for equal brightnesses the threshold 'pause' is longer than the threshold 'flash'. The difference is seen only with very short durations (6σ) requiring high illuminations, and tends to disappear at low illuminations. The fact that the eye is more light adapted in the light–dark-light series has probably something to do with his results. For time intervals between 6 and 30 σ the product of brightness and minimal duration of flash is constant. He compares his results with those of other workers. *Zipkin* (1915) measured the minimum perceptible dark interval in an otherwise continuous light. He confirms Gildemeister and Rutenburg. He used areas larger than the fovea. After about two minutes the fovea comes to a constant state of adaptation relative to the perception of light pauses; the periphery continues its course of dark adaptation for ten to fifteen minutes. As other workers have found, this does not hold for red light. He found that at any given adaptation level the threshold pause decreases as the light intensity increases. Moreover the product (intensity) × (duration of threshold pause) or the threshold light subtraction increases as the light intensity increases. There seems to be no summation effect for pauses which succeed one another at 0·7 sec. or longer intervals.

Cobb and *Loring* (1921) describe a method of measuring the 'sensitivity' of the retina which was later used by Cobb alone. As was stated earlier, Cobb believes that visual acuity as measured by Snellen's types tells us nothing of the true 'sensitivity' of the retina, but reveals only the 'dioptric power' of the eye. In test types the image on the retina is made up of areas with large differences of contrast. Cobb's experiments on difference thresholds have been described already (p. 29). In the present investigation they use the speed of impression by the retina as a measure of its sensitivity. A large white screen with a hole of 13·138 or 18·096 mm.^{2} cut in it was arranged so that a drop blind could cut off the illumination coming through the hole, so giving a 'negative' stimulus of known duration. The illumination of the large white screen was kept constant at about 3 foot-candles; this was done by repeated photometric measurements. The observer sat at a distance of 6 metres and fixated a point 2° from the object. A large number of determinations were made which were analysed by the method of serial groups.

The product of the 'time of exposure' and area of stimulus was found to be a constant quantity for any one observer. When a $(10\sqrt{2})$ sq. mm. aperture was employed the threshold time for his three best observers was found to be 25·7, 19·5, and 26·2 thousandths of a second respectively. It was found that shadows cutting off 40–60 per cent. of the light falling on the large white screen did not affect the results provided they did not fall across the central

portions. Using this apparatus *Cobb* (1923–4) did experiments both with and without illumination of the surrounding field. The angle subtended by the test field was 2·43 minutes, and the brightness of this patch could be varied from 3·2 to 340 candles per square metre. In each case the illumination of the surrounding field was adjusted to that of the screen over the test field so that the position of the latter was no longer visible.

The results are plotted for the reciprocal of the minimal light pause against the field brightness. The time varied from forty to seven thousandths of a second at the lowest and brightest illuminations respectively. The presence or absence of illumination of the surrounding field was found to have no constant effect. His results can be summarized in the formula $\frac{1}{t} = k \log \frac{B}{B_o}$, where t is the threshold time, B is the test-field brightness, and k and B_o are constants. There were marked individual variations. The maximum speed of discrimination had not been reached at 130 foot-candles. Higher intensities are required if the contrast is decreased.

Later he modified the apparatus and made a more complete investigation. He employed two rooms, in the first of which was the surrounding field with a 5·8° × 5·2° opening. Beyond this, in the smaller room, was a screen whose brightness was adjusted to that of the large screen. In the centre of this again was a circular opening subtending an angle of 2·43 minutes, into which the image of another screen was projected by a $+10\,D$ lens. This opening could be darkened for any desired length of time by a falling shutter. The subject fixated a black spot 2° to the left of the stimulus aperture. The threshold was taken as that time interval at which the observer recognized the darkening five times out of ten.

If instead of giving a preliminary exposure of a plain white surface before the exhibition of the dark pause, a grid pattern was first shown followed by a smaller grid pattern with the lines pointing in another direction, then different results were obtained. The speed of discrimination of the second grid pattern was in all cases about one-third of that obtained with the simple dark pause, and the increased power of discrimination with increase of illumination was not so marked; the higher the illumination the more marked the confusion caused by the after-image.

Ferree and *Rand* (1922) did experiments similar to those of Cobb, but they employed the broken circle test object subtending angles of 1·15, 1·73, 2·49, and 3.45 min. of arc. As before, speed of recognition was measured by the reciprocal of the recognition time. In all cases there was an increase in the speed of recognition with increased illumination, but the increase was more marked with the smallest test object and not at all marked with the largest.

Cobb (1922) attempted to find if there is any relation between a subject's speed of vision and his visual acuity as measured by Snellen's letters. One hundred and one subjects were used. He showed that although individuals differ considerably *inter se* and at different times under the same conditions, yet the variations between individuals are considerably larger than the individual's variations from time to time. This applied to both practised and unpractised subjects. The

practice effect was considerable; the probable error (in thousandths of a second) for a practised subject was 1·0, for an unpractised subject 1·7.

The test-type visual acuity was taken for each eye separately and for both together, and the correlations with the results obtained by his apparatus worked out by Karl Pearson's method. His most important conclusions were: (1) That the attempt to measure 'retinal sensitivity', using the apparatus described, in terms of visual acuity is futile. Retinal sensitivity as measured by his method 'involves a new characteristic of vision that is not to any significant extent taken into account in the measurement of visual acuity by means of a letter chart'. (2) That his 101 subjects could be divided into two groups, one of which had its maximum distribution at 27 thousandths and the other at 16 thousandths of a second. (3) Two series of readings were taken for 96 subjects. Correlation of the results of the first series with those of the second, taken immediately after the first, shows almost identical characteristics for the two. The correlation ratio is $0{\cdot}857 \pm 0{\cdot}018$. (4) The characteristic equation derived from correlation of the retinal sensitivity results (average of 1st and 2nd series) with visual acuity indicate that retinal sensitivity is somewhat dependent upon the visual acuity of the eye with poorer vision, but not upon that of the better eye unless the advantage of this latter is evident in enhanced binocular visual acuity. (5) Due allowance for the difference due to different visual acuity leaves individual differences in retinal sensitivity measurements unaccounted for, almost to the original amount. The standard deviation is reduced to 4·24 from 4·64 when correction is made for the differences due to different visual acuity. (6) The method of correlation indicates that binocular visual acuity is dependent chiefly upon the eye which, used singly, shows the better vision, to the extent of nearly five times its dependence upon the eye with the poorer vision. This has exclusive reference to results obtained with the letter chart. (7) There is no correlation between the results of retinal sensitivity tests and the disqualification of candidates on a rating based upon the ophthalmologic portion of the Air Service Medical Examination for flying status.

THE INFLUENCE OF ILLUMINATION ON THE DISCRIMINATION OF COLOURS

1. Differences of Brightness.

This problem has attracted many workers, since it is more easily investigated than hue differences and also because of its importance in equality-of-brightness photometry. *Lamansky* (1871) found that the just noticeable difference of brightness for colours has not a linear relation to the intensity of the light, but that the sensitivity decreases as the intensity of the stimulus is decreased. Here, as in allied problems, the sensitivity of the eye is defined as inversely proportional to the just noticeable change of the characteristic in question. The sensitivity of the eye for brightness was also found to be greatest for

yellow, followed by green, blue, and red, in that order. *Dobrowolsky* (1876, 1881) was concerned chiefly with peripheral vision, which he compared with that of the fovea. He worked at seventeen points of the intensity scale for different colours. The order of sensitivity was found to be blue, green, red, the sensitivity to blue being greatest. He measured the apparent brightness of the colour at each step. *König* and *Rittler* (1888), see *Luckiesh* (1921), and *v. Helmholtz* did careful work at this problem. *Ferree* and *Rand* (1916 *a*) found that at 350 mc. (?) the smallest brightness change which can be detected is 5 per cent. for spectral red (768–650 $m\mu$), and 10·4 per cent. for spectral blue-green (465–520 $m\mu$). The mean variations in setting from these values were 2·5 per cent. and 5·5 per cent. respectively. *Nutting* (1909) re-calculated *König's* data for the homochromatic difference threshold for brightness. The values found were, red 0·0376, yellow 0·0320, green 0·0252, blue 0·0250. *Crittenden* and *Richtmyer* (1916) estimated the precision of setting in the photometric comparisons of modern illuminants showing small colour changes.

Ives (1912), using a 4·58° field, determined the percentage mean variations of photometric equations by direct comparison between a 4·85 w.p.c. carbon lamp and various spectral colours. There were five observers. Some of his results are shown in Table XIII.

Table XIII.

	Per cent. Mean Variations in settings.	
Wave-length in mμ's.	76·0 *Photons.*	30·4 *Photons.*
653	8·3	5·6
632	6·3	4·3
622	6·5	3·3
612	4·5	3·9
594	3·7	3·1
574	5·2	2·2
555	4·7	4·1
545	7·9	4·9
535	3·1	3·6
517	7·0	4·43

The improvement at higher illuminations and the greater accuracy for the middle range of wave-lengths should be noted.

Troland (1918 *a*) measured the difference threshold between all possible paired combinations of eight spectral colours. The colours selected were the so-called psychological primaries and their intermediaries. He employed a field of 2·62° × 1·02°. The eye was kept adapted by the diffuse light of the room until the last moment before making a determination. The apparatus and the limits of wave-length of the patches employed are described in detail. Two subjects were used. The standard light, starting at a high value, was decreased in intensity by a rotating sectored disk until it was just noticeably brighter than the comparison field, and then three other readings—just not noticeably darker, just noticeably darker, and just not noticeably brighter—were taken. The results, expressed as fractions of the original brightness, are given in Table XIV.

TABLE XIV.

Values of the Heterochromatic Relative Threshold for Brightness Discrimination for one Subject.

Comparison Colour in $m\mu$'s.	Standard Colour. Blue 475 $m\mu$. 25 Photons.	Green 505 $m\mu$. 25 Photons.	Green 505 $m\mu$. 240 Photons.	Yellow 575 $m\mu$. 25 Photons.	Red 693 $m\mu$. 25 Photons.
460	0·174	0·147	0·175	0·191	0·191
475	0.075	0·159	0·108	0·201	0·195
490	0·121	0·116	0·165	0·161	0·191
505	0·126	0·0367	0·0226	0·185	0·214
520	0·129	0·122	0·140	0·126	0·190
550	0·129	0·144	0·152	0·125	0·185
575	0·118	0·173	0·082	0·0369	0·194
580	0·128	0·160	0·147	0·097	0·170
610	0·131	0·153	0·213	0·155	0·149
640	0·178	0·155	0·183	0·175	0·092
670	0·176	0·172	0·170	0·169	0·080
693	0·173	0·192	0·187	0·150	0·042

The most important conclusion is that the difference threshold for brightness is at its lowest when homochromatic patches are compared and that the threshold increases to a maximum of from five to ten times that for no colour difference when the latter is greatest, i.e. for the complementary colours.

The figures quoted were all reduced to a value corresponding to one for the homochromatic difference threshold, and they were then plotted against the number of just noticeably different steps of *hue* between the standard and comparison colours.

The curve obtained is that of the segment of an ellipse with a limiting value for red whose curve is a circle. A general psychological theory is outlined to explain the influence of colour differences upon luminosity discrimination, and the relation of this theory with the colour pyramid is discussed.

French (1919) measured the just noticeable differences for red, yellow, and green (filters), using lamps of 16, 100, and 400 C.P. The results indicate that for green light the just perceptible percentage increase of illumination is less the higher the illumination, and for red and yellow is greater the higher the illumination. The actual number of readings is not recorded. He plots the number of correct estimations against the percentage difference of brightness for the white, green, red, and yellow used. The angular diameter of the hole was 7 min. 50 secs. This is equivalent to calculating the mean error of setting and reveals that this is least for white and greatest for green with yellow and red intermediate in value, yellow being slightly better than red. Unfortunately, actual illumination intensities are rarely stated by this observer. *Geissler* (1913), *Jones* (1914), and *Neelin* (1913) have also worked on this problem.

2. HUE.

The smallest amount of light necessary to evoke the sensation of each spectral colour is of considerable theoretical importance and has attracted a corresponding amount of attention. Purkinje (1825) observed a series of pigment colours at daybreak and found their order of appearance in their true hue to be blue, green, yellow, and lastly red. *Aubert* (1862) illuminated 10 mm. squares of different coloured

pigment surfaces, the amount of light being adjusted by the size of a diaphragm admitting daylight. He makes a note of the size of opening necessary to evoke a sensation of colour and also the apparent hue. His results are given in Table XV.

TABLE XV.

Size of Opening in window in cm.^{2}	*Colour of Pigment used.*	*Colour Sensation evoked.*
$\frac{1}{4}$, $\frac{1}{2}$, 1	All	None
$1\frac{1}{4} - 1\frac{1}{2}$	Orange	Red
2	O.Y.R. Rose	O.Y.R. Rose
3	Blue	Blue
3	Light Green	Brown
$3\frac{1}{2}$	Light Green	Light Green
5	Green	Blue
8	Green	Green

He also worked with 60 mm. squares, with similar results.

At these threshold illuminations various factors have important influences on the discrimination of the eye for colours, e. g. the state of adaptation [Charpentier (1877, 1896)], the size of surface employed [*Hueck* (1840), *Wolffberg* (1887), *Charpentier* (1888), v. Helmholtz, v. Frey, v. Kries (1881), Hering (1893), *Haycraft* (1897), Loeser (1905), *Abney* (1913)], the background on which the colour is viewed and the presence of neighbouring sources of light [*Aubert* (1862, 1865), *Fick* (1888), *Angier* (1907), Boswell (1907), *Rand* (1913), *Haupt* (1922), *Granit* (1924–5), *Schulte, Technische Hochschule, Berlin* (1925)].

Fick found that if a field of coloured light is reduced in size till it appears colourless, its colour may be restored if other equally small areas are simultaneously illuminated with the same light. The threshold value for colours is lower when a feeble source of light is exhibited in the vicinity ; this may be white or any light with a high scotopic value such as green (Boswell). Aubert showed that blue is recognized earlier on a white than on a black background and vice versa for green. For details of the above work see *Parsons* (1924).

A suggestive piece of research was done by *Blanchard* (1918), who measured the smallest brightness of a coloured source of light which would evoke a sensation of colour when viewed with a surrounding field of varying brightness. The size of test field employed was 5° diameter and its brightness could be varied from 10^{-7} to 10^2 millilamberts (controlled by a wedge) ; the surrounding field's brightness could be varied from 10^{-7} to 10^3 millilamberts. The same general result was obtained as with white light (see section on Lateral Illumination). There are, however, two points of interest : first, that for very bright surrounds a larger increase was required in the case of white light than for any of the coloured lights, and secondly, at a brightness corresponding to that of an interior at night the smooth course of the curves was interrupted temporarily in the case of blue and green and a greater relative threshold brightness is required than for any other colour or for white.

The effect of different intensities of illumination on the field of vision for colours has been much investigated on account of its bearing on the theories of colour vision. Amongst those writers who have made special reference to the degree of illumination may be

mentioned *Raehlmann* (1872, 1874), Butz (1881), *Wolffberg* (1885), *Aubert* (1862), Chodin (1877), *Abney* (1913), *Rand* (1913) (this paper contains a full bibliography and abstracts), *Dobrowolsky* (1876), *Dreher* (1912), *Ferree* and *Rand* (1920 *a*)).

It was seen from the work of Aubert that at low intensities of illumination the physiologically impure colours tend to be misnamed as pure colours. At sufficiently high intensities of illumination there is again a general falling-off of discrimination, all spectrum colours tending to become yellowish white [*Peddie* (1922, p. 85), *Haupt* (1922), see below, *Abney* (1913)]. *Peirce* (1877) has shown that of two patches of monochromatic light of the same wave-length, the brighter appears the yellower, and that the dimmer light can be made to match the brighter in hue by a change in wave-length. A wave-length of 582 $m\mu$ when sufficiently brilliant is whiter in appearance than a dimmer patch of the same wave-length.

It is often stated that between blinding intensities on the one hand and threshold intensities of light on the other, the degree of illumination has no influence on hue discrimination [e.g. *Laurens* and *Hamilton* (1923)]. Most of the investigations on the just noticeable differences of hue have been done at one brightness [*Mandelstamm* (1867), *Dobrowolsky* (1872 *a*), *Peirce* (1877), *Peirce* (1883), *König* and *Dieterici* (1884), *Uhthoff* (1888), *Brodhun* (1892), *Exner* (1902), *Rayleigh* (1910), *Edridge-Green* (1910, 1911), *L. A. Jones* (1917), *Priest* (1920). That of *Steindler* (1906) is the most important: see *Parsons* (1924).]

Houstoun (1918) used a method of Edridge-Green (1910, 1911) for mapping out the number of monochromatic patches in the spectrum. He discusses in some detail the defects of the method and points out that by the use of a double-image prism to bring the brighter end of one image into contact with the darker end of the other, the width of the monochromatic patch can be decreased to one quarter. This phenomenon is also found in the great yet unapparent difference in brightness between the central and peripheral fields of cheap telescopes. The disagreement in results between different observers may be due in part to the sizes of field used. This factor is an important one at low illuminations. On the whole, Houstoun accepts the method as a rapid means of estimating a subject's colour perception.

He found that when the brightest part of the spectrum has an illumination of 500 metre-candles the number of monochromatic patches is seventeen. When the illumination is reduced to 64 metre-candles, the number of monochromatic patches is twelve, and when further reduced to 2 metre-candles, the number of patches is seven. He himself could discriminate seventeen patches, a performance which he repeated a year later, although the limits for each patch were different. His observations on fatigue will be found on page 57. *Edridge-Green*, on the other hand, found that fewer hues can be discriminated at low intensities than at high.

Haupt (1922) investigated the relation between the apparent saturation of pure spectral colour with respect to different physical intensities as measured by a theromopile. He used the apparatus of Ferree and Rand with certain modifications. Precautions were taken to obtain the colours pure. The amount of light transmitted was

regulated by three Kodak filters in conjunction with rotating sectors. The outer set of sector disks had a radius of 19·5 cm. and the inner set a radius of 17 cm. By this means the field was bisected; one half was used as a comparison field and the other was variable. The measurements were taken both with dark surroundings and with surroundings equal in brightness to the field under consideration. The eye was dark-adapted for 15 minutes before each set of readings, it being assumed that the two to three seconds' exposure given subsequently did not materially alter the level of adaptation. He used patches of wave-length 656 $m\mu$, 616 $m\mu$, 580 $m\mu$, 553 $m\mu$, 522 $m\mu$, 488 $m\mu$, and 463 $m\mu$. The values were checked frequently by a Hilger direct-vision spectrometer, a desirable proceeding since he used a carbon bisulphide prism. The energy densities were measured at the threshold and at the point of apparent maximum saturation of the colours. The intermediate energy values were calculated from the sizes of the sectors, and are given in Table XVI.

TABLE XVI.

Wave-length in $m\mu$'s.		Energy in Watts $\times 10^{-15}$ required to arouse a sensation of colour (threshold), measured at analysing slit (?). Dark Surrounds.	Light Surrounds.	Energy in Watts $\times 10^{-8}$ to reach point of maximum saturation at analysing slit.
Red	655	173·34	91·53	7656·81
Orange	616	239·80	158·78	2679·88
Yellow	580	154·84	227·96	1196·55
Y.-green	553	63·81	29·77	348·46
Green	522	18·59	16·20	287·24
Bl.-green	488	96·71	172·76	141·26
Blue	463	69·50	51·05	131·85

He then determined the intensity at which the variable field appears just more saturated than the comparison field. 'For these just noticeably different determinations the outer disk was moved so as gradually to increase the value of the open sector until the right half of the field appeared just noticeably more saturated.' For the descending series, i.e. when increased intensity of light causes a decreased saturation of the colour, the outer disk was opened wide and closed gradually until the two fields appeared just equally saturated. He does not appear to have found any difficulty in dissociating the concomitant changes of brightness from these saturation changes. By 'stepping' the saturation in this way he finds the number of just noticeable differences required to reach the maximum of saturation. These are given in Table XVII.

TABLE XVII.

	Dark Surrounds.	Light Surrounds.
Red . . .	40	80
Yellow . . .	21	46
Green . . .	32	70
Blue . . .	35	71

In the descending series, blue loses its saturation most rapidly, whilst red and green retain their characteristic colours to very high intensities. He believes with Geissler that the number of J.N.D.'s required to reach the point of maximum saturation may be used as an indication of the degree of saturation at its maximum.

He measured the inherent brightness of the colours at their point of maximum saturation by an equality of brightness method with a standard white (Table XVIII).

TABLE XVIII.

	Dark Surrounds.	*Light Surrounds.*
Red . . .	7·66	16·87
Orange . . .	8·79	7·86
Yellow . . .	1318·45	1162·88
Yellow-green . .	6·39	3·47
Green . . .	9·49	6·21
Blue-green . .	2·62	2·91
Blue . . .	0·95	1·30

The changes of hue were noted and described at certain J.N.D. steps from the threshold, with the light surrounding field (Table XIX).

TABLE XIX.

Number of J.N.D. steps from threshold.	*Colour observed when the stimulating patch had the given wave-length.* 655 $m\mu$ (*R*).	580 $m\mu$ (*Y*).	522 $m\mu$ (*G*).	463 $m\mu$ (*B*).
0	Red	Olive-green	Blue-green	Purple
6		Distinctly green		
10	Brownish	Yellow-green		
18		Greenish yellow		
26		Yellow with tinge of green		
30	Brownish red			
36		*Good yellow* (Beyond this a yellowish white.)		
49				*Blue* (Passing into white beyond this.)
50	*Good Red*		*Pure Green* (Progressively yellowish beyond this.)	
80	Bright scarlet			
82	Orange tint (Orange pink beyond this.)			

Kramer (1882) measured the distance at which 4 mm. squares of blue, yellow, red, and green had to be placed from the eye in order that their colour could be recognized under different illuminants. The red square was seen at a greater distance for all lights except calcium, for which green is seen at a greater distance. All colours were recognized at a greater distance in sunlight than for any of the other illuminants (candle, gas, petroleum, sodium, calcium, strontium, and calcium lights). As the intensity of the artificial light is decreased the coloured squares had to be placed nearer to the eye. He ignored the factor of simultaneous contrast.

Laurens and *Hamilton* (1923) made an elaborate and careful series of experiments to ascertain the effect on the hue sensibility to different

spectral wave-lengths of: '(1) Intensity of illumination, that is whether the positions of the minima shift with varying intensity. . . . (2) The size of field. (3) The order in which pairs of wave-lengths are presented to the observer. . . . (4) The effect of selective and of general fatigue.' The first determinations were similar to Steindler's, a great point being made of equating the two comparison fields for brightness. In this series the field was at a uniform brightness of 1·5 millilamberts (four photons at the retina) throughout. They used Nicol prisms for reducing the intensity of the beams. The field of view was 3° in diameter, one portion being illuminated by one light source and constant deviation prism, and the other by a separate light source and prism. The field was divided by a Lummer-Brodhun cube. The spectrum was stepped in both directions, i. e. from red to blue and from blue to red. The total number of discriminable hues was 161 for one observer and 207 for the other. They found that the points where hue discrimination is best occur at 620–630 $m\mu$, 565–587 $m\mu$, 480–496 $m\mu$, 433–448 $m\mu$, but these vary from person to person and in the same person on different occasions. The results agree fairly well with those of Steindler. When scaled from blue to red there is an indication of an additional minimum at 520 $m\mu$.

They determined also the wave-lengths which their subjects judged came under the headings of the standard colour names. This was done at three brightnesses. In Table XX the names given to the colours of the spectrum when seen in sequence from blue to red and from red to blue are quoted. The wave-lengths are the longest to which the name opposite was given.

TABLE XX.

	Red to blue.		*Blue to red.*	
Names of Colours.	*Average for red end of colour in $m\mu$.*	*Average variation in $m\mu$.*	*Average for red end of colour in $m\mu$.*	*Average variation in $m\mu$.*
	(20 millilamberts at 590 $m\mu$.		*Average of 7 observers.)*	
Red end	772·5	±14·2	750	±6·0
O-R	637·5	12·5	601·9	15·2
O	614·4	15·6	585·6	11·7
O-Y	602·8	13·9	571·2	12·5
Y	591·9	9·4	557·5	13·8
Y-G	575·0	10·0	531·3	18·8
G	532·5	14·4	507·1	12·4
B-G	505·6	12·1	488·6	5·9
B	481·9	11·9	465·6	13·8
B-V	461·9	8·4	447·9	4·4
V	443·8	10·0	431·3	6·8
End	405·1	4·9	410·6	5·7
	(5 millilamberts.		*4 observers.)*	
Red end	705	±10·0	726·3	±11·3
O-R	626·3	8·7	596·3	1·8
O	598·7	3·8	586·3	3·8
O-Y	591·2	4·1	565·0	10·0
Y	583·7	1·9	553·8	6·7
Y-G	576·3	3·8	536·3	16·3
G	551·3	4·1	518·8	18·8
B-G	525·0	15·0	501·3	18·8
B	493·8	13·8	471·3	14·4
B-V	477·5	2·5	455·0	35·0
V	470·0	0·0	438·3	22·2
End	425·0	23·8	421·6	15·5

Names of Colours.	Red to blue. Average for red end of colour in mμ.	Average variation in mμ.	Blue to red. Average for red end of colour in mμ.	Average variation in mμ.
	(1·25 millilamberts.		2 observers.)	
Red	700·0	±0·0	705·0	±15·0
O-R	630·0	10·0	600·0	0·0
O	597·5	7·5	595·0	0·0
O-Y	592·5	7·5	585·0	10·0
Y	582·5	2·5	555·0	0·0
Y-G	575·0	5·0	550·0	35·0
G	547·5	7·5	535·0	0·0
B-G	535·0	5·0	517·0	17·0
B	495·0	10·0	477·5	2·5
B-V	480·0	0·0	470·0	0·0
V	470·0	0·0	445·0	0·0
End	432·5	32·5	430·0	0·0

The positions of the points of greatest hue discrimination are unchanged by changes of illumination. It will be noticed, however, that the colour name given to a wave-length changes with the direction in which the spectrum is scaled. This difference is due to successive contrast. When, however, the two fields were set at points of just noticeable difference of hue, simultaneous contrast became evident and the direction of the spectrum in which the colour pairs were shown was of no account. The results were quoted in full. One point of interest arises : in the region of the green and yellow, and to some extent as far down as the blue-green, it was found that the names given to the contrasted colours were rather far apart in the hue scale. Their work on fatigue is given in another section, page 57.

Göthlin (1922) determined the extent of the purely yellow zone in the spectrum. It was found to vary from 574 to 596 $m\mu$ with different individuals. The maximum number of votes was given for 580 $m\mu$. Some subjects were sure to within $\frac{1}{2}$ $m\mu$, others to within 10 $m\mu$.

The influence of contrast and general illumination on colour recognition is an important one, but a systematic survey of the literature will not be attempted. Amongst the more important papers may be mentioned *Rollet* (1867), *Schmerler* (1883), *Hering* (1887), *Kirschmann* (1891), *Pretori* and *Sachs* (1895), *Fröhlich* (1921 *b*), *Ferree* and *Rand* (1912, 1916 *a* and *c*), *Cook* and *Kunkel* (1916), *Crane* (1917). Kirschmann's law states that colour contrast is best observed when brightness contrast is eliminated or reduced to a minimum.

The desaturation of colours by white light has been studied by *Draper* (1879) and *Rood* (1880). *Nutting* and *Jones* (see Luckiesh, 1924) measured the just noticeable decrease in saturation at different colour saturations. *Jaensch* (1919–21), *Kroh* (1921), and *Marzynski* (1921) have written on the tendency to name the colours of objects according to our previous experience of these objects and irrespective of their illumination.

Hartridge (1913), in the course of his work on the absorption bands of haemoglobin, discusses the factors which affect the measurement of absorption bands in general. The individual variations were found to be considerable. The initial intensity of the light, the value of visual threshold, as affected by dark adaptation or previous exposure to a bright light, and contrast all affect the apparent positions of the edges of the bands. In the case of the yellow edge of the α band of oxy-haemoglobin, it was found that its edge shifted gradually from

581·2 $m\mu$ to 586·8 $m\mu$ as the intensity of the incident light was decreased to 1/128, its initial value. The edges of the band for the normal eye are at 582·9–571·2 $m\mu$, for an eye which has been rested in the dark 581·1–572·6 $m\mu$, and after stimulation by bright light 584·5–569·4 $m\mu$. The factors mentioned above are extremely important in the discrimination of the colours of dyes with a single blunt absorption edge. The argument is developed in a later paper (1920): 'The changes (in hue) for a given alteration of concentration are greater the flatter and broader the absorption band. If, therefore, there are two pigments of the same concentration and the same colour, one of which had a sharp well-defined band, while that of the other was broad and flat, the latter pigment would be found to give the more accurate readings in the colorimeter', since an equal increase in the thickness through which the solution is viewed will bring about a greater change of hue in that solution with the blunt cut absorption band.

VISUAL FATIGUE

One would expect to find very little work of a quantitative nature on a subject with such a vague name as fatigue. There appears to be practically none which is not related to colour vision. Visual fatigue has been treated from three points of view: (*a*) the after-effects of exposure to certain adverse conditions, (*b*) the after-effects of exposure to white lights varying in quality and quantity, (*c*) the after-effects of exposure to coloured lights.

Attempts have been made to define and classify the effects of fatigue. *Jackson* (1921) gives three criteria as to the presence of fatigue: (1) Retinal fatigue as evidenced by lower visual acuity. 'This dropping of visual acuity begins very soon after the eyes are brought into use. We find habitually that a patient with the eye properly focused gets his best vision on first looking at the test cards, after a slight period of rest. If he does not utilize it and attempts to decide on doubtful letters by steadily looking at them, he makes more and more mistakes. Often the patient almost says the right letter or quite utters it, and then immediately changes his mind and says something else.' (2) Closely related to his lowered visual acuity is the fatigue significance of after-images. (3) Failure of co-ordination by the extra-ocular muscles.

Ferree (1914–15) and *Ferree* and *Rand* (1915 *a*) state that a good test of fatigue is the ratio of the time of clear to unclear vision of a test object. They think that fatigue is localized in the muscles of the refraction mechanism and that it is not retinal. For its highest efficiency the eye requires 'the field of vision uniformly illuminated and no extremes of surface brightness'. Under correct illumination the eye maintains a practically constant efficiency for from three to four hours. The effect of poor systems of lighting 'is not so great, however, on the ability of the fresh eye to see clearly as it is on its power to hold its efficiency'. Under an illumination that gives 'maximal acuity for the momentary judgement, the eye runs down rapidly in efficiency'.

These writers in a later paper give their further views on the causes of ocular fatigue (1925 *d*). Most of the diseases of the eye

are attributed to defects in artificial illumination, which is supposed to produce a maladjustment between the amount of accommodation, convergence, and the size of the pupil. As regards the discomfort due to glare they state that the 'sensitivity for certain parts or zones in the peripheral field is greater than that for the centre; that the sensitivity is in general greater for the temporal than for the nasal half of the field, and for the lower than the upper half; and that in passing from the centre to the periphery the sensitivity is found first to increase, then to decrease, becoming extremely little at the limits of the field'.

Mosso (1915), in his book on fatigue, has a great deal to say on the subject of fatigue of the eye, which is attributed to several different conditions: cerebral anaemia, retinal anaemia, and muscular fatigue of any of the extra- or intra-ocular eye muscles. Retinal anaemia can be demonstrated by pressing the sclera whilst gazing at an illuminated surface; after about ten seconds only a much diminished sensation of light will be received. Mosso's observations apply in 'general bodily and mental fatigue'.

Some other writers have speculated on the anatomical site of fatigue. *Lasareff* (1923) quotes figures to show that the strength of a faradic current necessary to produce a sensation of light on stimulating the sclera is constant whatever the time during the course of dark and light adaptation. According to this, the site of fatigue must be peripheral to the ultimate distribution of the optic nerve fibres, and not in the eye centres in the cortex of the brain.

Troland (1916 *b* and *c*) uses the word 'minuthesis' for the 'depression of a sensation under the influence of a stimulus, to replace the word "fatigue"'. He gives measurements of the time required to produce a just discernible minuthesis for different colours at the same intensity. In addition he measures the time required for the retina to reach a condition just indistinguishable from that of equilibrium. 'Given a sufficiently long exposure, the visual system reaches a state of equilibrium with respect to any stimulus which may be acting upon it, and in this state the eye yields a sensation which is not subject to further minuthesis.' The paper has no reference to the lasting effects of fatigue.

1. The Effects of Exposure to Adverse Conditions.

The Manual of the Medical Research Laboratory U.S.A. 1918, 1919 gives a method of testing candidates for the Air Service which will be described elsewhere (p. 63). The tests are repeated under conditions of oxygen-want. The average results of performance are given.

Breton (1920), in the course of a discussion on range-finders and their use, states that 'in from twenty minutes to half an hour under good weather conditions, most observers tend to fail progressively in the accuracy in their "cuts", so that if a ship is continuously in action for much longer periods, either the range takers must have periodical relief or her gunnery practice will deteriorate'. The 'cuts' referred to consist in aligning the two halves of the same images seen through separate object-glasses. In the case of observation on a post the procedure is comparable to the setting of a vernier. He states that

there is no evidence as to how long it takes for fatigue to appear in the use of stereoscopic range-finders. *Hanson* (1920) discusses the effect of bodily posture in reading and the use of telescopes.

2. The Effects of Exposure to White Light.

Most of the work under this head has been done with a view to ascertaining the best types of illumination fittings (luminaires). Much of it, on the immediate effects on eye, is wrongly called 'ocular fatigue'; the influence on visual performances of a bright unguarded light near the line of sight, for instance. The observations on these immediate effects are to be found in the section dealing with the effects of lateral illumination on the eye. The work on luminaires, again, deals for the most part with the question as to whether a given source of light is 'restful' or 'annoying' to the eyes. If the feeling it produces is one of pleasantness, it is assumed that used over long periods it will produce no ill effects. If, on the other hand, there are strong contrasts or blinding light sources, it is assumed that 'eye-strain' or 'ocular fatigue' will follow. *Gould* (1920) classifies occupations according to the percentage of employees suffering from 'eye-strain'. He says the grouping has 'the value only of my guesses'. He gives a formidable list of diseases due to this 'eye-strain'; it includes 'tics, choreas, epilepsies, and lateral spinal curvature'. Other writers on 'ocular fatigue' and 'eye-strain' are *Baur* (1912), *Alger* (1913), *Lancaster* (1914), *Kerr* (1916), *Oblath* (1924).

Kaz (1914) made observations at different illuminations to determine the maximum contrast which could be employed in order not to interfere with the recognition of test objects. The maximum contrast allowable is greater at high than at low illuminations. With the illumination of the brightest part at 2·44 M.K. the maximum contrast is 1 to 8; 8·96 M.K., contrast 1 to 28; 133 M.K., 1 to 56; 515 M.K., 1 to 110. An apparatus is described for making these measurements.

Other writers dealing with the effect of fatigue on reading are *Griffing* and *Franz* (1896), *Dearborn* (1906), and *Wager* (1922), the first dealing more especially with the effects of illumination and colour.

3. The Effects of Exposure to Coloured Lights.

'Earlier authors, including v. Helmholtz, and most physicists, make free use of the conception of fatigue to account for successive induction, but the facts, and especially those of simultaneous contrast, negative so simple an explanation. There is, however, a group of phenomena associated with prolonged or intense stimulation to which the term may be fittingly applied, though even in this case it should be done "without prejudice". These phenomena have been studied particularly by Burch' [*Parsons* (1924)].

The phenomena observed after comparatively short exposures of the eye to coloured light seem to differ in degree rather than in kind from the forms of intense stimulation referred to above, and since they are generally known as fatigue effects a brief review will be given of the more important papers. The subject has been investigated by *Darwin* (1786), *Aubert* (1858), *v. Helmholtz*, *Hess* (1890),

Katona, *Burch* (1898–1913), *Edridge-Green* and co-workers (1910), *Watson* (1913), *Fröhlich* (1921 *a*), *Abney*, and others.

Hess (1890) worked at eleven points in the spectrum and investigated the hue changes in the remaining ten when the eye was fatigued to each in turn. He employed fatiguing lights which were not too large and observation fields which were not too feeble. After fixing his eye on the edge of a 6° fatiguing field for ten or thirty-five seconds he turned his eye on to a patch illuminated by one of the eleven spectral colours and observed the change of hue. As an illustration of his results and also because of the discussions on the effects of fatigue on this part of the spectrum the observations for 575 $m\mu$ (yellow) will be quoted. When the eye was fatigued to this colour for ten seconds 700 $m\mu$ became bluish red; 600 $m\mu$ inclined to red; a green of 554 $m\mu$ inclined to yellow; a green of 525 $m\mu$ inclined to blue; 500 $m\mu$ became blue-green; 490 $m\mu$, bluish green; 475 $m\mu$, blue; 422 $m\mu$, more blue; and purple, red-blue. After thirty-five seconds' fatigue 700 $m\mu$ became blue-red; 600 $m\mu$, bluish red; 554 $m\mu$ and 525 $m\mu$, blue-green; 500 $m\mu$, almost pure blue; and the rest of the colours blue. Yellow, 575 $m\mu$, appeared the following colours after fatigue to each of the wave-lengths stated; 700 $m\mu$, greenish yellow; 600 $m\mu$, yellow inclining to green; 554 $m\mu$, 525 $m\mu$, 500 $m\mu$, and 490 $m\mu$, yellow inclining to red; 475 $m\mu$, yellow; 422 $m\mu$, yellow inclining to green; purple, bluish purple; yellow became greenish yellow.

Burch, in a series of papers (1898–1913), describes the effects produced on his eye of very intense retinal stimulation by coloured lights. The sun's rays were focused by a 2 in. focus burning-glass on to the pupil so as to fill it completely. The colour was got by the interposition of various dyes: a ruby glass backed with a magenta-stained film for red; three thicknesses of green glass coloured with cupric oxide for green; a tank filled with ammonium copper sulphate for violet; and for blue, the blue prismatic spectrum. After fatiguing the eye in this way he observed the effect on the colours seen through a single prism spectroscope illuminated by the sky. The red from *A* to *B*; the green from the neighbourhood of *E*; the blue about half-way between *F* and *G*; and the violet at and beyond *H*, produced well-defined and characteristic results. The intermediate portions of the spectrum produced results intermediate in character, that is fatigue to orange and yellow; blue-green and indigo produced changes similar to those produced by fatigue to the colours on either side of them. After fatigue to red, green, pure blue, and pure violet he found: '(1) All direct sensation of the colour used in fatiguing the eye is practically lost, not merely from the corresponding part of the spectrum, but also from those regions in which it overlaps the other colours. (2) The colour used for fatiguing the eye produces a positive after-effect of the same colour like a luminous fog, by which the hue of all the other colours is modified if they are relatively weak but is unnoticed if they are bright. This effect is strongest in the violet and weakest in the red. After light from *A* to *B* all sensation of red vanishes. The spectrum begins between *C* and *D* with pure green. The blue and violet are unchanged in extent, but look a trifle warmer in tone. After light from *D* all sensation of both red and green vanishes, the spectrum beginning with blue just

beyond the *b* lines. The violet looks very brilliant and extends quite as far as usual. After light from *E* all sensation of green vanishes, and the red meets the blue and overlaps it between *b* and *F*. There is a strong subjective green glare which, if the slit is nearly closed, makes the red look orange and the violet dull and dirty, but on opening the slit the red resumes its natural colour. After light from about half-way between *F* and *G* all sensation of blue vanishes, the violet meeting the green and overlapping it at about the same part of the spectrum. There is a strong subjective blue glare making the red look slightly crimson with a narrow slit. The violet extends as far as usual but is more ultramarine in tone. After light from between *H* and *K* all sensation of violet vanishes, the spectrum ending with a pure blue of great brilliancy about midway between *G* and *H*. The green and red have their usual limits, but with a narrow slit the red appears bright purple and the green almost white.

'During the condition of blindness to any one colour it is possible to blind the eye to any of the remaining colour sensations. Thus after light from *A* and *B* combined with light from *G* and *K*, only the green sensation is left, the spectrum extending strongly from *D* to *F* and more faintly to *C* in the one direction and nearly to *G* in the other. Similarly after light from *G* to *K* followed by light from *E*, only the red sensation is left. It extends from *A* to a little beyond *b*.'

On the basis of these experiments, Burch came to the conclusion that there are four primary colour sensations, red, green, blue, and violet. For a criticism of this assumption see *Rayleigh* (1899).

Edridge-Green and *Marshall* (1909) criticized Burch's results on the grounds that the fatiguing light was strong enough to produce pathological effects. They 'produced fatigue by using a sodium flame and staring at it for some minutes. . . . On exposure of the eye to the sodium flame for from three to fifteen minutes and then looking at the spectrum we found the yellow entirely obliterated, and only a faint band of orange separated the red and green, but if the eye were still further fatigued this also was obliterated, and the red and the green met without anything whatever intervening.'

'The red looked rather more purple; the green was slightly tinged with blue. The blue and violet at first appeared greatly diminished in intensity but not changed in character. There was no shortening whatever of the red end of the spectrum; it terminated at precisely the same place as it did previous to the eye being fatigued with the yellow light. If one eye only were exposed the other remained perfectly normal and could be used as a control.' With one eye protected with a piece of red glass, which was found on spectroscopic examination to transmit red rays only, 'we looked intently into an incandescent electric lamp, and on looking into the spectroscope we found the red obliterated as red. It was shortened to from half to three-quarters of its extent, and here we were unable to see any light at all; the part we could see was changed to orange'; the true orange became yellow, and the yellow, yellowish green.

'Fatiguing the eye with green light caused the yellow and blue to encroach on the green. If the eye were saturated with blue light the blue disappeared and the violet and green met.' If saturated

with violet light, the violet became indistinguishable from the blue, and the real blue became greenish.

Porter and *Edridge-Green* (1912) continued their researches fatiguing the eye for twenty seconds with a fatiguing light which was much stronger than the reacting light. The projected after-image of the colour was made to fall down the centre of a spectrum on a screen for the whole of its length. The length of time allowed before taking the readings is not apparent. After fatiguing the eye by pure red light (654–675 $m\mu$), the extreme red was 'slightly diminished', and there was no perceptible action on orange, yellow, and green. Blue and violet became much darker and bluer. When a filter was used so that only red and orange appeared on the screen, the red 'disappeared' whilst orange remained. 'After exposure to 654 $m\mu$ to 675 $m\mu$, orange-red [*sic*], a sodium flame was viewed and found to be very little affected in the region of the after-image (no effect *A.W.P.*) (slightly green *E.-G.*) though the green-blue after-image was very strongly marked on either side of the sodium flame.' After fatigue to 619–631 $m\mu$ (orange), a dark blue after-image was seen right across the spectrum except in the region of the orange, which appeared unaffected. Fatigue to 585–595 $m\mu$ (orange-yellow), 545–550 $m\mu$ (yellow-green), and 496–500 $m\mu$ (blue-green) gave a purple after-image seen right across the spectrum, the red being affected most; fatigue to 475–480 $m\mu$ (blue) gave a reddish purple after-image and no action on red and orange; fatigue to 445–455 $m\mu$ (blue) gave an after-image of yellow-green (*A.W.P.*) or orange (*E.-G.*), and the violet and blue were cut off whilst green and red appeared yellower; fatigue to 425–436 $m\mu$ (violet) gave a green after-image, which made the violet and blue appear green, and made the green appear a slightly yellower green, and did little or nothing to red or orange. They conducted a further series of experiments using a different brightness of the reacting light. Space does not permit the results being quoted.

Burch (1913 *a* and *b*) criticized Porter and Edridge-Green's results on the ground that the stray light in the rooms rendered the colours impure. He maintained that this stray light, especially the violet, will explain their results, and that after fatigue to red it is a common observation that yellow does change to green except to the green-blind.

Edridge-Green (1921) in a dark room free from stray light, and using a 1,000 C.P. Pointolite to form a colour patch, investigated the effect of red fatigue on the white equation. Fatigue was induced by looking at a 100 C.P. Pointolite with a condenser through a piece of deep red glass allowing rays of greater length than 600 $m\mu$ to pass. A patch made up of thirteen green, thirty-six red, and forty-two violet which ordinarily appeared white, appeared a brilliant green after thirty seconds' red fatigue. To produce a white after fatigue eight green, thirty-six red, forty-two violet were needed. 'There seems to be considerable variation in the length of time necessary to cause fatigue with different persons.'

Wanach (1908) believes that the eye fatigues more quickly to the less refrangible spectral colours than to the more refrangible. Fatigue lasts longer at the macula than at the periphery. He eliminated

stray light entering the eye through the sclera which could have accounted for the results.

Woog (1919) found that the persistence of retinal impressions is longer for the centre than for the periphery of the retina.

Abney (1913) made a very complete investigation into both the hue and luminosity changes after fatigue to white and coloured light. Space does not permit of his results being dealt with adequately; the original work, or Parsons (1924 *b*) for the theoretical aspect, should be consulted. A few examples only will be given here. The method employed was to fatigue one eye with a spectral colour, and then to gaze on a patch illuminated by a reacting colour. The change in hue was judged by comparison with a similarly illuminated patch visible to the unfatigued eye only. The results are given in Table XXI.

TABLE XXI.

Reacting Colour.	*Fatigue time 30 seconds. Luminous intensity of fatiguing patch about 2 candles, 1 foot from the screen.*		
about.	*Red Fatigue.*	*Fatigue with 598 mμ.*	*Fatigue with 540 mμ.*
670 $m\mu$	Same colour, but darker	No change; a little darker	A little darker
647 $m\mu$	,, ,, ,,	Colour a little darker	,, ,, ,,
590 $m\mu$	Greener and slightly darker	No change, only darker	Slightly darker
540 $m\mu$	Green; slightly bluer	Bluer and darker	Darker: no change in colour
515 $m\mu$	Green; slightly bluer	Much bluer and rather darker	Slightly bluer
489 $m\mu$	No perceptible change	Slightly bluer	Bluer and darker
442 $m\mu$	Bluer than unfatigued	No apparent change in colour, but darker	No visible change in colour
All the violet	Much bluer and darker	Bluer and darker	Slightly dimmer

'The general results that are obtained from these fatigue experiments in the spectrum are as follows. When the eye is fatigued by red, the red itself is reduced in luminosity; the orange becomes yellow; the yellow greener; whilst the green, owing to the inherent white, becomes a bluer green; the blue-green is not so much affected; the blue becomes greener and the violet becomes bluer green. When the eye is fatigued by green, the red remains unaltered; the orange becomes redder, as does the yellow; the green becomes paler and at one part nearly white; the blue-green becomes bluer, the blue more violet, and the violet unchanged. Fatigue by a patch of blue is more difficult to induce. The principal change is in the blue-green, which becomes greener and the violet redder.' He points out that after fatigue to about 580 $m\mu$, where the red and green sensations are equally stimulated, a colour composed of red and green sensations will not alter in hue.

'If a dazzling green ray falls on a place in the retina, we have the green sensation at its maximum stimulation at once, and following quickly on we have the red and blue sensations contained in the ray at their maximum stimulation. When the three stimulations are equal, the effect is to produce the sensation of white. The green

would thus appear nearly white, with a slight tinge of green in it. From the sensation composition of an orange ray, which is red and green, we should find, on using the same argument, that the dazzle colour of the orange would be very bright yellow of a hue in which the two stimulated sensations are equal.'

Houstoun (1918) found that when he was very tired he could map out only 14 homochromatic patches in the spectrum, whereas normally the number was 17 or even 19 when he was feeling very fit. (See p. 45.)

Hamilton and *Laurens* (1923), in a continuation of their paper on brightness discrimination (see page 47), did a careful and exhaustive series of experiments on the eye's ability to discriminate *differences* of hue after fatigue to spectral colours. A fatiguing field of 4° diam. and a reacting field of 3° diam. were employed. Fatigue to red was induced by gazing at a field of about 650 $m\mu$ (brightness 85 millilamberts) for thirty seconds. After this the eye was directed on to the reacting spectrum (about one photon) and the two halves of the field were adjusted to equal brightnesses, and the smallest perceptible difference in hue measured. This performance was repeated to make sure that no recovery from fatigue had taken place. From the single minimum at about 480 $m\mu$ the curve rose steadily to a maximum about 620 $m\mu$, where wave-lengths 30 $m\mu$ apart could be only just distinguished as differing in hue. The following names were applied to the colours: 650 $m\mu$ unsaturated reddish; 630 $m\mu$ green; 550 $m\mu$ green. For fatigue with green (517 $m\mu$) a field brightness of 52 millilamberts was employed, the other conditions being unaltered. There were 2 minima at about 430 and 520 $m\mu$. The latter value was also obtained in their previous paper, but was not noted by Steindler. Blue fatigue to 460 or 440 $m\mu$ and a field brightness of 3 millilamberts gave indications of 2 minima.

They also investigated the effect of 'non-selective fatigue', i. e. where one sensation was not affected more than another. As fatiguing lights they used: white, a 3° field on a piece of ground glass illuminated by a 100-watt gas-filled lamp 50 cm. away; orange-red of 630 $m\mu$ and 156 millilamberts; yellow of 570 $m\mu$ and 342 millilamberts; blue-green of 480 $m\mu$ and 9 millilamberts. The hue discrimination curves do not differ markedly from the normal except that the average threshold is higher and the orange minimum is lost in all, and the violet minimum in some. The colour names were unaltered.

They measured the increase in brightness which it was necessary to give to a patch of colour of the same wave-length as that to which the eye had been fatigued, in order that it should equal in brightness a patch of colour of different wave-length but which before fatigue was equally bright. They varied both the fatiguing brightness and the reacting brightness. The results for one observer are given in Table XXII.

TABLE XXII.

Fatiguing Light. Wave-length.	Fatiguing Light. Intensity in millilamberts.	Composition of test field in $m\mu$'s.	Intensity of reacting fields to unfatigued eye in Photons.	Per cent. increase of Homochromatic stimulus to match Heterochromatic stimulus as seen by fatigued eye.	Colours of the two test fields as seen by fatigued eye.
650 $m\mu$	85	650 and 460	0·07	1730	G : B
			0·77	248	Y-grey-G : B
			7·5	0	Deep O-R : B
		650 and 517	0·07	1730 to 2340	Black : G
			0·77	248 to 336	Pink : G
			7·5	37 to 63	R : G
517 $m\mu$	52	517 and 460	0·175	200	
			0·4	110	
			0·7	0	
		517 and 650	0·175	207	
			0·4	103	
			0·7	0	
570 $m\mu$	342	570 and 460	0·33	289	
			0·63	66	
			3·06	53	
			4·68	0	
		570 and 517	0·33	300	
			0·63	70	
			4·06	30	

'It is to be emphasized that in addition to the differential brightness fatigue which has just been discussed, there is also a general fatigue which affects all colours in the spectrum, no matter with what light the eye had previously been fatigued. For example, after red fatigue a red-blue test field would appear much dimmer to the fatigued eye than to the normal eye.'

'Adaptation' to Colour. Closely related to the subject of the after-effects of exposure to coloured lights is that of adaptation to colour. *Aubert* found that coloured objects appear colourless in both direct and indirect vision if the stimulus is sufficiently long continued. According to Brücke the light-adapted retina is normally adapted to red. *Exner* (1868) found that three parts of the spectrum are much less altered in appearance by adaptation fatigue than other parts, namely, red from the end of the spectrum to between the lines *C* and *D*, green between *E* and *b*, and blue about *G*. The effect lasted about ten seconds. *v. Kries* (1882, 1905), on the other hand, found that yellow (560 $m\mu$), green (500 $m\mu$) and blue (460 $m\mu$) changed least in hue, red and yellow-green changing in the direction of yellow, whilst blue-green and violet changed in the direction of blue. With long fixation a colour loses in brightness as well as in hue. *Hess* (1890) found that for prolonged fixation of a colour it becomes less and less saturated (mixed with its complementary) and finally disappears; also that the complement of the fatiguing colour always remains unchanged in hue. *Allen's* transition points, i.e. the points in the spectrum after fatigue to which the spectral colours remain unaltered in brightness, are at 660 $m\mu$, 570 $m\mu$, 470 $m\mu$, 420 $m\mu$. *Sheppard* (1920) found that all colours become grey in appearance if fixation is sufficiently prolonged. The subject sat in front of a large coloured screen lighted by bright sunlight or by a bright light indoors. The times taken to reach this grey stage are given in the Table XXIII.

Table XXIII.

Colours.	Sunlight. Relative Luminosity.	Sunlight. Time for Adaptation.	Artificial Light Relative Luminosity.	Artificial Light Time for Adaptation.
R	18	194·1 sec.	22	91 sec.
O	34	91·1 ,,	20	90 ,,
Y	55	45·9 ,,	18	95 ,,
Y-G	46	51·3 ,,	28	61 ,,
G	37	50·6 ,,	32	56 ,,
B-G	30	119·8 ,,	40	40 ,,
B	12	220·0 ,,	12	120 ,,
V	22	209·3 ,,	30	81 ,,

Similar determinations were made with pure spectral colours. An artificial pupil was used. 'The amount of light that entered the collimator of the spectroscope was 61·4 C.P.' He claims that the curves obtained for 'adaptation' almost coincide with Abney's spectral luminosity curves. The colours did not proceed to neutral grey if the light entering the spectroscope was less than 60 C.P.; if the light was more than 100 C.P. there is 'pain' on fixing a coloured object. He also used coloured filters in front of an arc light. The adaptation times are longer than with a spectroscope and moderate illumination.

By the appearance of the screen at different times he judges that the fovea has a longer adaptation time for colour than any other part of the retina. This law apparently holds for high intensities as well as for medium and low intensities. Brightness is not the determining factor in the 'adaptation' time, but 'chroma'. Adaptation is rapid at first and then slower. The experiments do not succeed with small coloured areas because of the difficulty of maintaining fixation, especially towards the end of the time.

Troland (1921) did similar experiments with coloured papers of the Hering and Milton-Bradley series. He noted the change of colours for a period of one minute. A large field of $60° \times 50°$ was used. The results are given in part in Table XXIV.

Table XXIV.

Stimulus Colour.	Intensity candles/metre².	Colour Phases. Initial.	Colour Phases. Intermediate.	Colour Phases. After 1 minute.	Remarks.
R (Hering)	50,000	wr′	wr	w′r	Revival of red
Y (,,)	130,000	gy	g′y	g′y	
G (,,)	80,500	wg′b′	wgb	wgb	Moments of grey
B-G (,,)	31,000	b′w	b′w	b′w	
Purple (,,)	37,500	w″rb	w″rb	w″rb	

Abbreviations: w = lack of saturation, w′ = slight lack of saturation, gy = equally green and yellow, g′y = yellow stronger than green, g″y = yellow much stronger than green, &c.

His conclusions are (1) that prolonged exposure to large chromatic stimuli of high (but not maximal) intensity does not lead to a disappearance of hue; (2) that the qualitative change that does occur occupies a short time, and that there may be recovery during the stimulation; (3) that with very high intensities complete disappearance of the characteristic hue may ensue soon after the beginning of exposure. This does not involve the abolition of all chromatic quality, and never leads

to a grey sensation ; (4) that if a small white or grey object is introduced into the colour field in the above experiments the colour of the field is suddenly restored. This is interesting in connexion with Allen's work.

Troland did a further series of experiments with a large field as before, but each half covered with a differently coloured paper. As would be expected there was far less desaturation of the colours.

Akin to this problem of the change of hue and brightness of large coloured areas is the phenomenon of the apparent disappearance of white and coloured areas of feeble illumination on prolonged fixation. This has been investigated by *Lange* (1888), *Marbe* (1893), *Ladd* (1898), *Dunlap* (1921), *Ferree* (1906, 1913), *Troland* (1921), and *Heinrich* and *Chwistek* (1906). *Marbe* found that a coloured light of moderate intensity appears to vanish for a very short period of time only. If of feeble intensity it either disappears completely or fluctuates (Ladd). This may be because the fovea is physiologically blind for feeble illuminations. *Dunlap* found that there is disappearance with eccentric fixation; the darker and smaller (6 in. diameter or less) the light spot the quicker it goes. *Ferree* found that small areas do not disappear, whereas large areas do: this is attributed to eye movements. *Troland* found that large areas do not disappear completely, but only wane. He explains the results of other experimenters as due to alterations in the size of the pupil. He did some experiments where the subject increased the illumination every time the spot disappeared and so got the minimal illumination necessary for constant perception. A table was given of the minimal threshold at which each spectral colour just does not disappear.

Incidental references have been made to the alterations of brightness after fatigue in the section dealing with hue changes. Grünbaum, Allen, and Hollenberg have made determinations on the brightness of colours after fatigue, using the flicker method. This has the advantage that it is not a comparison method, but it has the disadvantage that it assumes that the equation for the time of persistence of retinal impressions with change of brightness is valid when the eye is under changing conditions. Used to compare the fatigue effects on different colours it is extremely useful. *Grünbaum* (1917) measured the critical frequency of flicker for the same light 45, 90, and 180 seconds after exposure to a constant light (see Parsons, 1924, p. 129). *Allen* (1919–25) and also *Hollenberg* (1924) have measured the critical frequency of flicker, i. e. the brightness of spectral colours after fatigue to a number of colours. Allen did this using the same eye for the fatiguing and measurement of brightness, and also exposing one eye to a spectral colour, and measuring the brightness of colours with the other ('Reflex Visual Sensations'). His results cannot be cited in detail. Briefly they are: that fatigue to red, green, or violet 'caused one elevation in the part of the spectrum corresponding to itself', that is, the brightness of those colours was diminished when viewed subsequently to the fatigue. 'The remaining colours each caused two elevations which were pairs of those obtained with simple colours. It was found that when the retina was fatigued with the four colours 660, 570, 470, and 420 $m\mu$ the normal and fatigue curves coincided, and these transition points were believed to mark the boundaries

between the simple and compound colors.' Shining a coloured light into one eye caused the 'reflex' excitation of all three sensations in the other or in different parts of the same eye, but particularly of the same colour as the exciting colour. In the case of six colours (660, 570, 520, 505, 480, and 425 $m\mu$) it was also found that 'the direct and reflex effects balanced or neutralized each other, so that even after prolonged exposure of the eye to their influence, all colours of the spectrum were seen without diminution or enhancement of brightness. In consequence these hues were termed equilibrium colours.' As regards the state of adaptation of the eye it was shown that the brightness of spectral colours was greatest when both eyes were rested normally in daylight, but if the eye not being used to take the measurements was blindfolded the brightness of the colours was decreased. If both eyes were rested in a completely darkened room the brightness of colours was diminished still further, whilst it was minimal when both eyes were kept in a dimly lighted room. Allen's results give a most satisfactory explanation of colour contrast.

Amongst papers on after-images may be quoted *Miles* (1915) and *Troland* (1916 and 1917). *Dobrowolsky* and *Gaine* (1876), in their investigations on peripheral vision, found a marked effect of fatigue. They used Snellen types and twelve subjects. The type was much more easily read in the peripheral field of vision if it was moved. Their subjects showed a marked practice effect.

For theoretical discussions of colour fatigue in the light of modern knowledge see *Parsons* (1924) and *Peddie* (1922).

METHODS AND APPARATUS

1. Test Objects.

Hay (1919), using a type of his own, determined the ease with which the various letters could be read when of equal size and viewed at the same distance. He recommends the use of the easiest letters in standard test types.

Sheard (1921) quotes the recommendations of the American Medical Association as to the construction of test types, and also makes some suggestions of his own. In both cases all the letters are used. Sheard draws attention to the fact that there are individual variations in the ease of reading the several letters. *Hartridge* and *Owen* (1922) made a complete investigation on themselves using Green's type. The actual mistakes at each distance were recorded. They find that there is a group of letters of medium difficulty which differ very little in the ease with which they can be read; these letters are recommended for the construction of test types. The results agree with the expectations from a consideration of visual acuity findings, with gratings, &c. *The British Journal of Ophthalmology* (1920) discusses the illumination of test types.

Löhlein discusses the value of visual acuity tests. *Meisling* (1919), *Dor* (1920), *Richter* (1920), *Schwartz* (1920), and *Pacalin* (1921) describe the use of new test objects, particularly for children. *Amman* (1922) emphasizes the importance of peripheral vision as an aid to the

central vision involved in the testing of visual acuity. Edridge-Green also mentions this fact.

Ives (1910 *a*) describes a test object made by superimposing two finely ruled gratings which, on rotation one over the other, give a series of dark bands on a grey background. The distance between the bands is given by $\frac{d}{2\sin\frac{1}{2}\theta}$, where d is the spacing of each grating and θ is the angle moved through. The advantage of this test object is that the size of the detail only is variable, and that this variation is gradual. In (1916 *b*) he described a new form of this device in which the two single line gratings of the earlier form are replaced by cross-line gratings, which, when rotated with respect to each other, present a pattern of uniformly distributed squares which expand or contract when the gratings are turned. *Lux* describes the Raster photometer for rapid measurements of illuminations by a visual acuity method. The test object is that described by Ives.

Kirsch (1920) describes the Zeiss optical apparatus for measurements of visual acuity. In this instrument the size of a projected image of a letter can be varied at will, so overcoming the defects of ordinary test types where some letters are more easily read than others. *Contino* (1922) points out one of the disadvantages of Snellen's types as a measure of visual acuity, namely that the graduation is not gradual. He uses the 'E' test. The observer is five metres from the nearer of two convex lenses through which he observes the letter. The position of the other lens is then gradually altered until the observer can just recognize the direction in which the letter points. He gives a formula for the ratio between the angular size of the image and that of a letter visible at five metres by an eye with a visual acuity of one.

Dunlap (1915 *a*) gives an account of the 'duoscope', an instrument which is 'not sensitive to brightness changes over a considerable range' but to adaptation changes, and may be found useful as an 'adaptometer'.

Xilo (1920) describes the use of nigrosin solutions (A.M.D.) made by Bayer for the reduction of the illumination when used in a glass-sided wedge. *Ferree* and *Rand* (1920 *b, c, f*) describe the apparatus used by them in their investigations on visual acuity. The test object was a Landolt broken circle which could be rotated into any desired direction. The gap subtended an angle of one minute to the observer. The illumination was varied by an adjustable diaphragm. *Henry* (1925) has devised an apparatus for the clinical determination of the light minimum and difference.

2. The Artificial Pupil (see also elsewhere).

Cobb (1911) and *Ferree* and *Rand* (1916 *c*) describe the method of forming an image of the analysing slit of the spectroscope upon the pupil of the eye. By this means the amount of light entering the eye can be regulated; the method can be used instead of an artificial pupil. *Troland* (1915) describes the use of the artificial pupil and a method of securing rapid and accurate concentric registration when used binocularly. No artificial pupil is of any use for

test objects subtending more than 53°. The paper contains an account of the theory.

3. The Testing of Personnel.

The Manual of Medical Research, Washington (1918 and 1919), describes a method of testing Air Service personnel. The test object consisted of a one-inch square of grey paper mounted on a two-inch square of lighter grey. There were thirteen perceptible differences between the two squares. A photometric wedge was drawn slowly across the sight-hole until the test object just ceases to be distinguishable. For threshold determinations of colour and light, the test object was a 3 mm. diameter aperture in the iris diaphragm of the light source. The time allowed was five to eight seconds. Some average results are given. *Herlitzka* (1919) determined the visual capacity of aviators by presenting a black pattern on a white ground after previous stimulation by white. *Ferree* and *Rand* (1919) describe a method of testing the speed of adjustment for clear seeing of the eye at different distances. They claim it should be used in the routine examination of the eyes of airmen, &c., see p. 10. *Cantonnet* (1919 *a* and *b*) describes tests for aviation candidates which include quickness of perception, sensitivity to dazzling, night acuity, and dark adaptation. For a discussion of the subject see *Spearman* (1919). *Baeumler* and *Hess* (1920) describe the testing of railway personnel.

4. Colour.

Ferree and *Rand* (1916 *b*) describe a campimeter in which the stimulus is spectral light of known wave-length and intensity, and can be presented at any point of the meridian of the retina. *Kirschmann* (1916) advocates the use of gelatine light filters in colour work, since by this means large areas can be illuminated.

Papers concerned with the radiometry of colours are *Coblentz* (1911), *Ferree* and *Rand* (1912), *Nutting* (1919), and *Priest* (1918), and with spectrophotometry, *Tufts* (1907), and *Dittler* and *Satake* (1914).

The following papers will be found useful to those not acquainted with the technique and terminology of optical investigations: *Trolantd* (1917 *a*, 1918 *b*), *Nutting* (1920 *b*), *Dow* (1924), and *Cobb* (1916 *a*), whose paper is written for 'investigators in those branches of biological sciences which deal with light effects'. *Sheard* (1921, 1924) deals with the subject chiefly from the clinical point of view.

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